

Professor Charles A. Whitten

Levoca, Slovakia, 2007



- One of the founders for STAR Experiment
- A genuine experimentalist
- A true gentleman

(selected)

Recent Results from STAR

Nu Xu

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(²) College of Physical Science & Technology, Central China Normal University, China





Outline



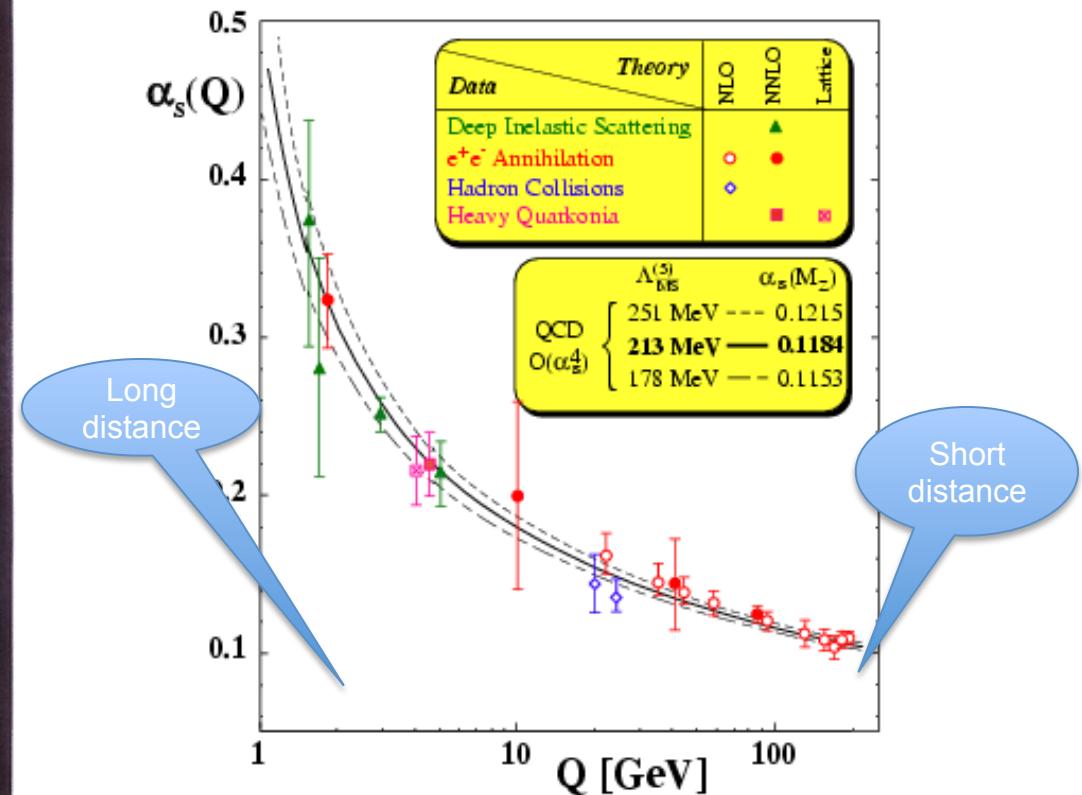
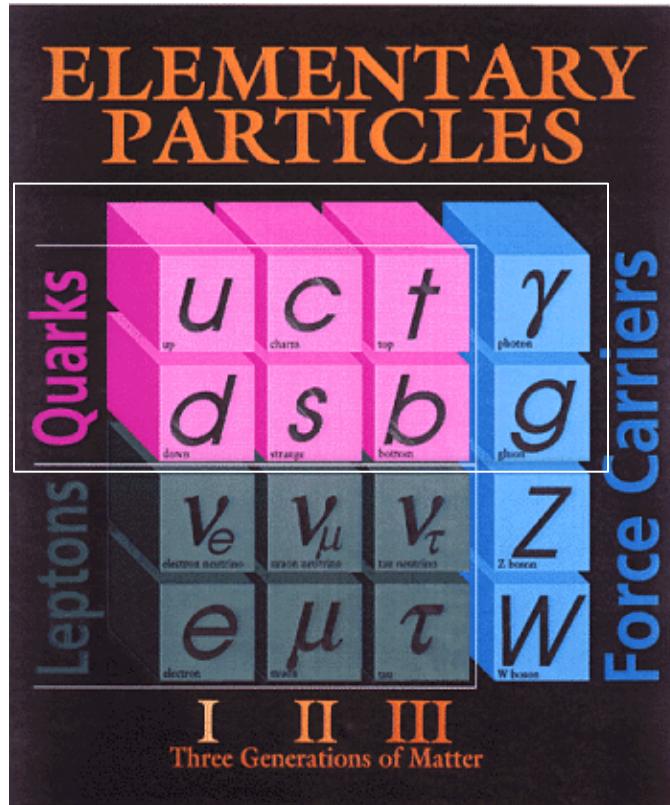
(1) Introduction

(2) Recent Results from RHIC

- Spin Physics
- $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au Collisions
- RHIC Beam Energy Scan

(3) Summary and Outlook

Quantum ChromoDynamics



- 1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
- 2) Little is known regarding the dynamical structures of matter with q, g .
E.g. the confinement, nucleon spin, the QCD phase structure...
Large α_s , strong coupling – QCD at long distance.



STAR Collaboration

STAR Collaboration

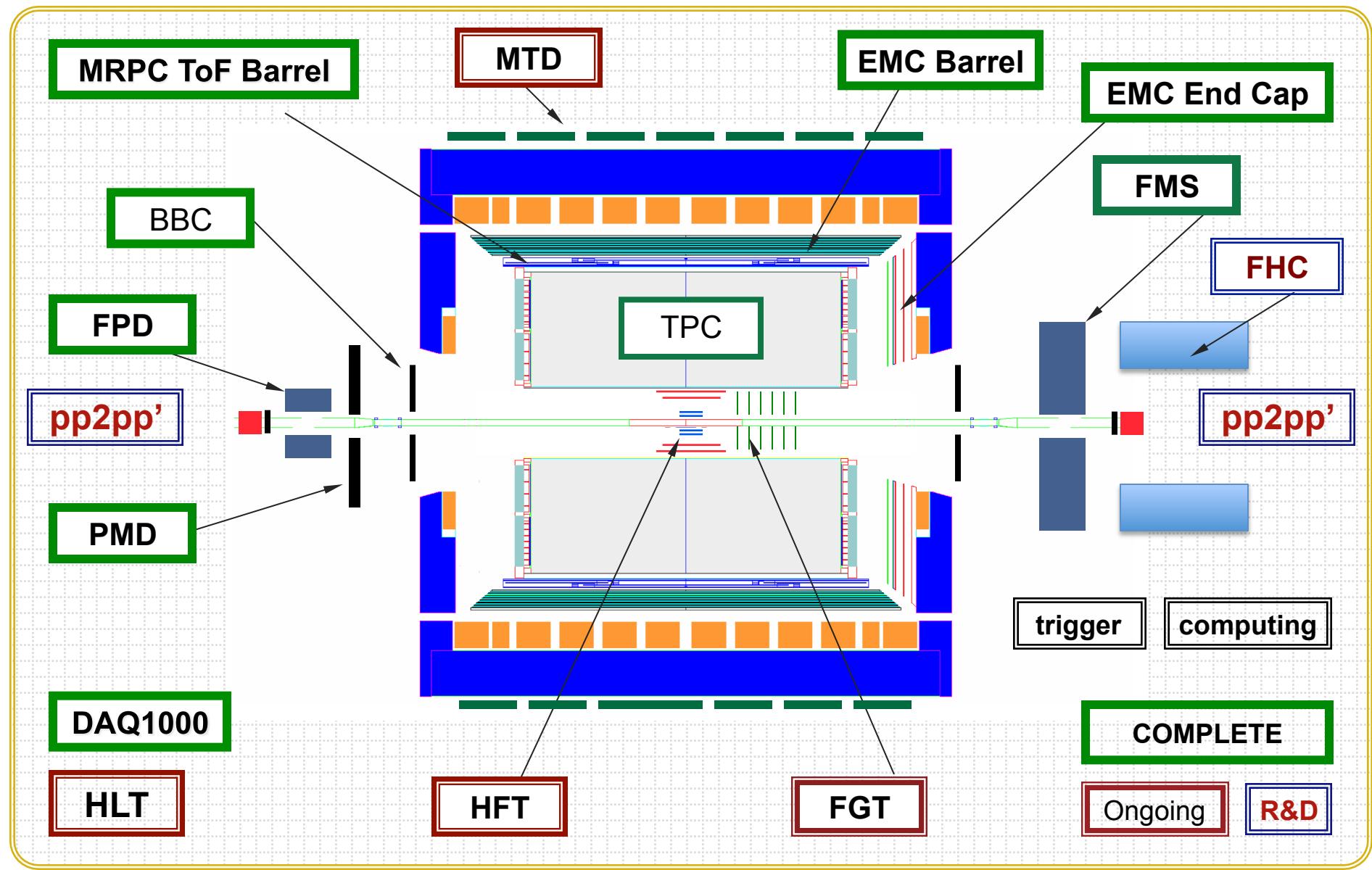
550 Collaborators

55 Institutes

12 Countries



STAR Experiment



MRPC Time Of Flight

EMC+EEMC+FMS
 $(-1 \leq \eta \leq 4)$

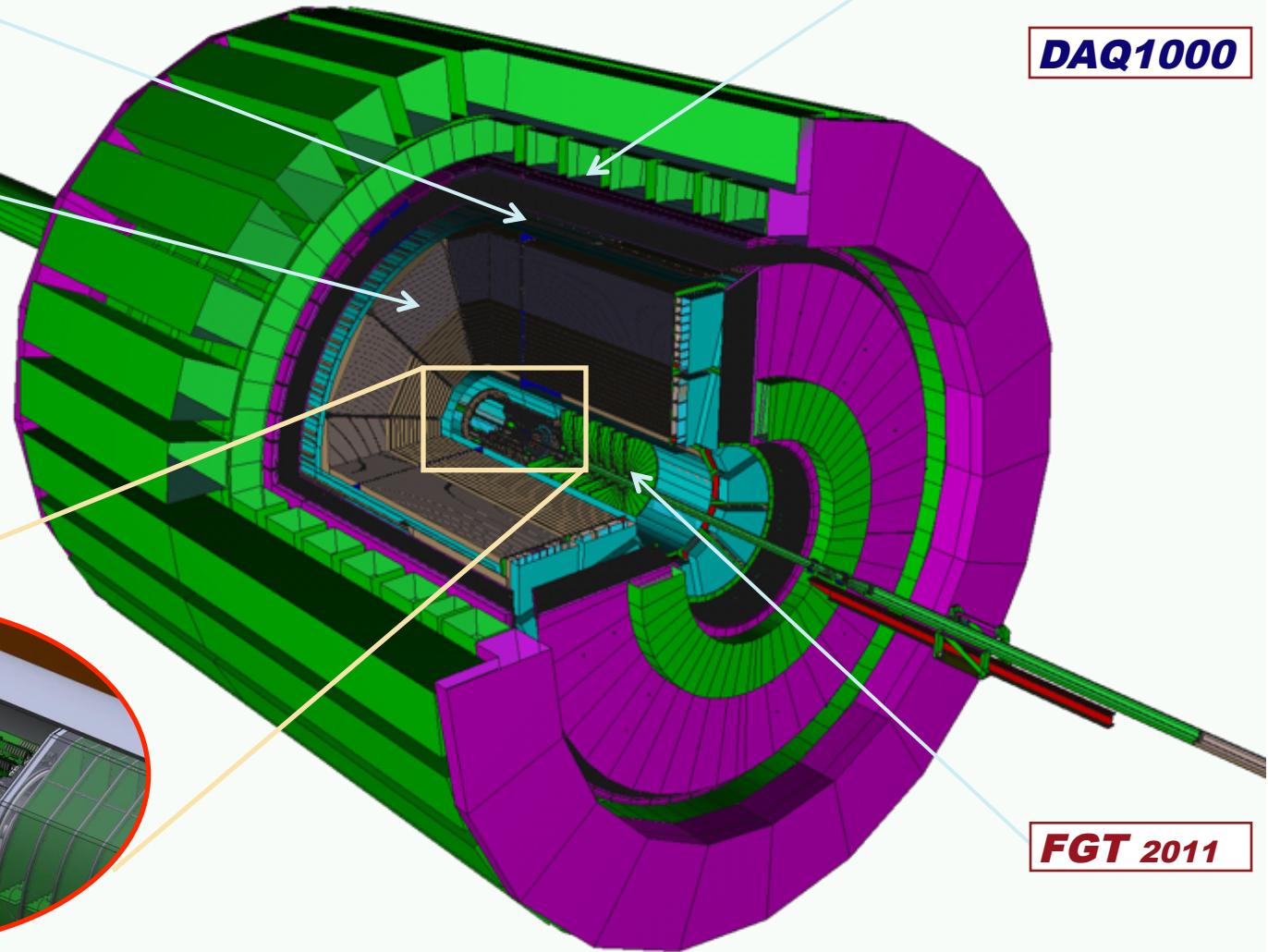
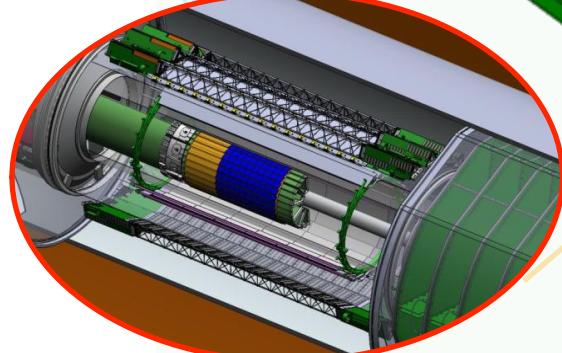
MTD 2013

Time Projection Chamber (TPC)

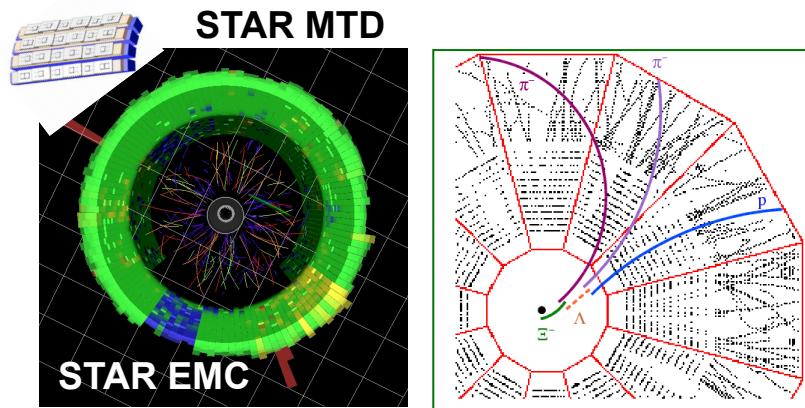
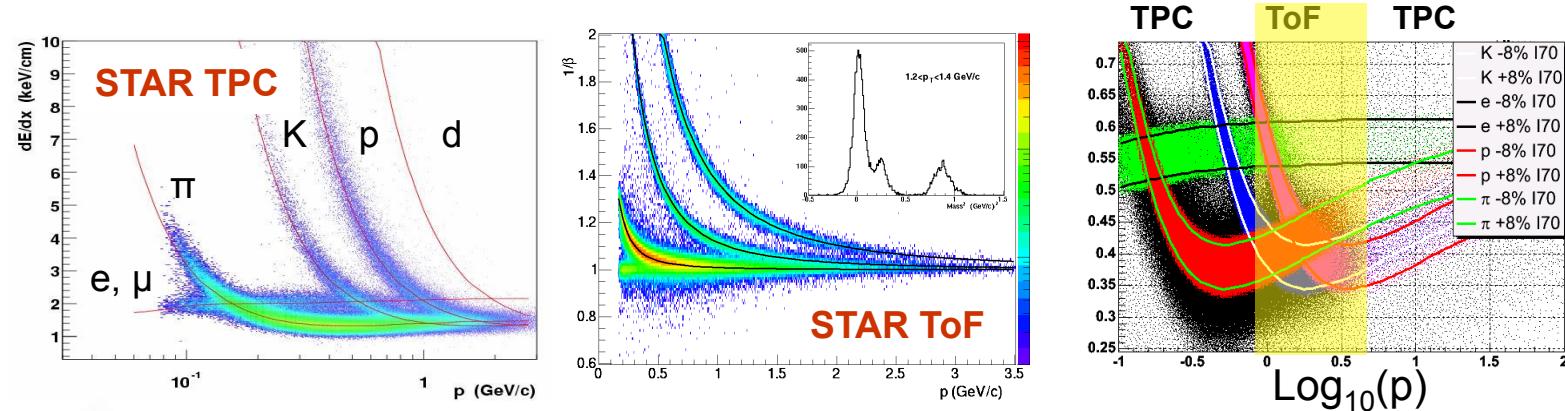
DAQ1000

**Heavy Flavor Tracker (HFT)
2013**

FGT 2011

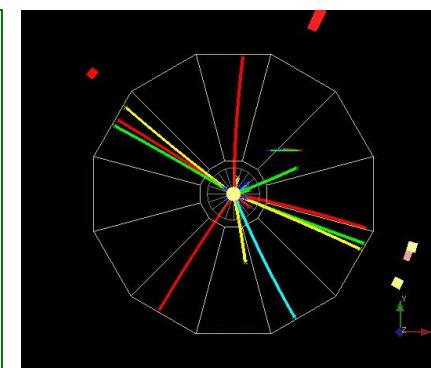


Particle Identification at STAR

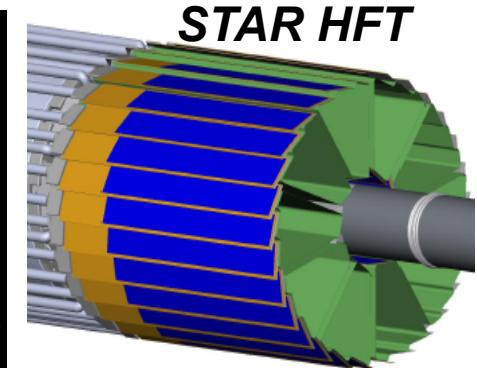


Neutral particles

Strange hyperons



Jets



Heavy Quark Hadrons

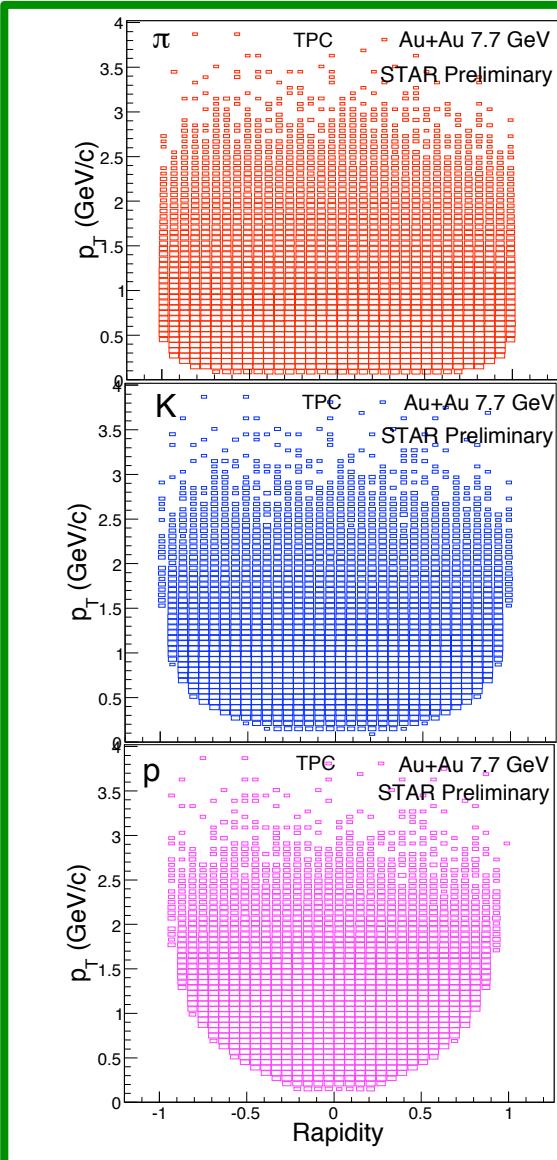
Multiple-fold correlations for both HI and Spin physics!



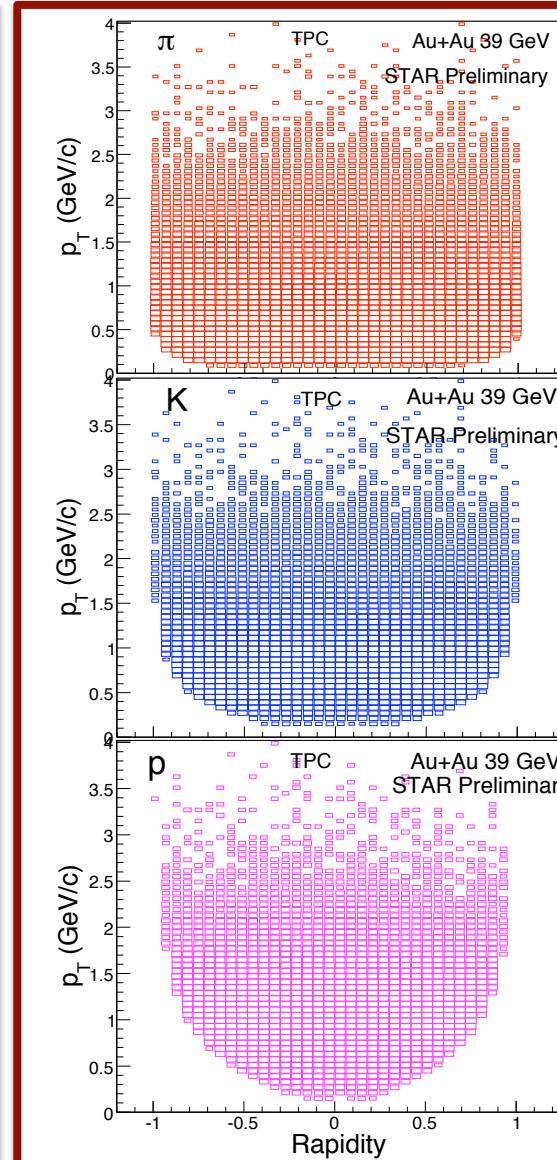
STAR PID: (π , K , p)



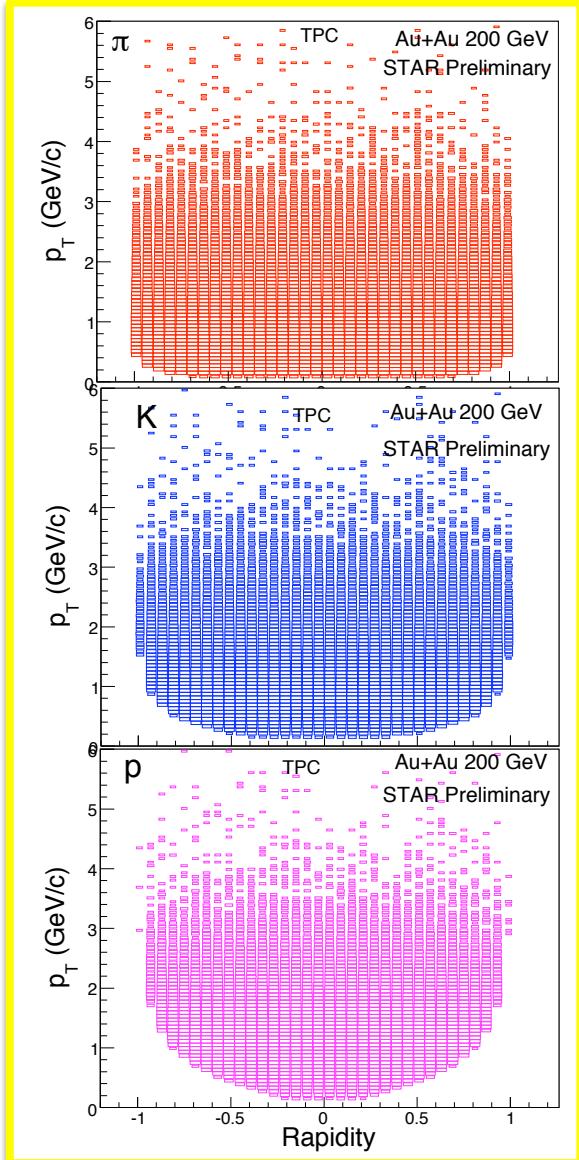
Au+Au at 7.7 GeV



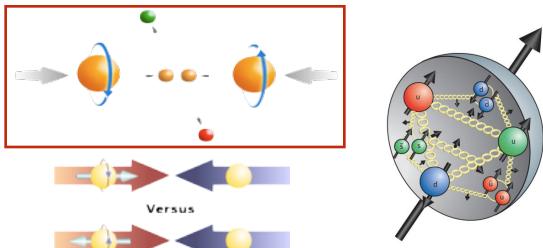
Au+Au at 39 GeV



Au+Au at 200 GeV

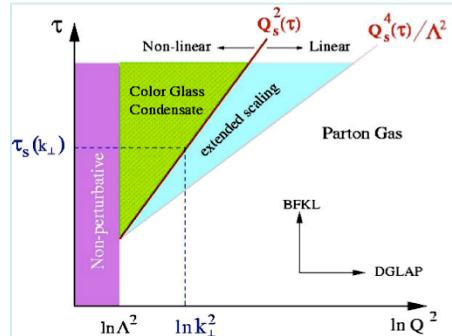


RHIC Physics Focus



Polarized $p+p$ program

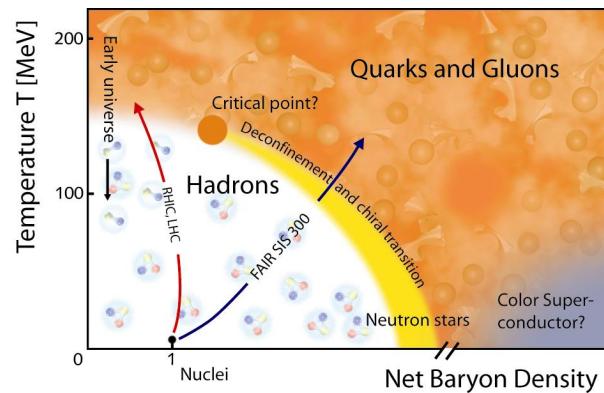
- Study *proton intrinsic properties*



Forward program

- Study low-x properties, initial condition, search for **CGC**
- Study elastic and inelastic processes in pp2pp

2020 -
eRHIC
(eSTAR)



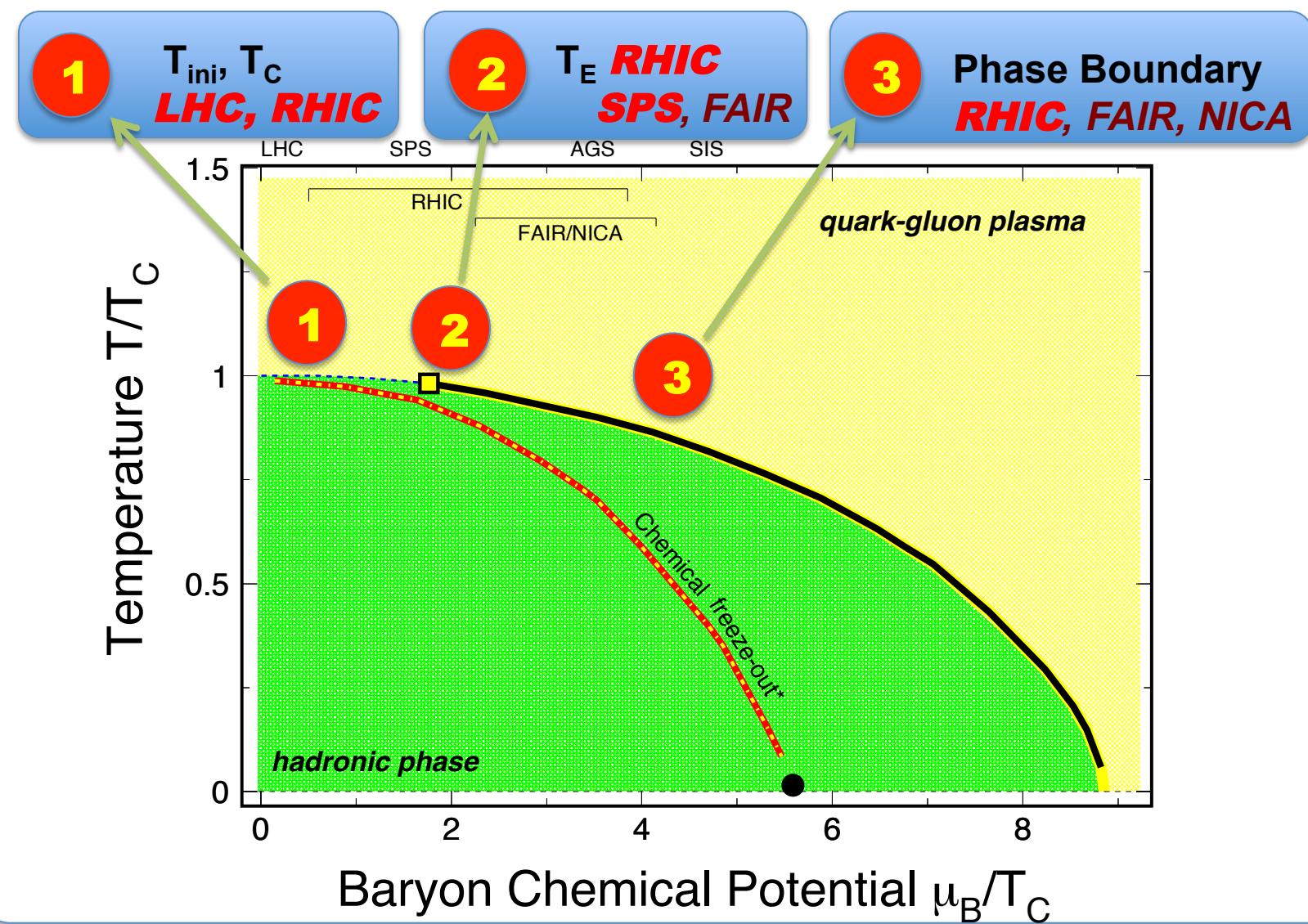
1) At 200 GeV at RHIC

- Study *medium properties, EoS*
- pQCD in hot and dense medium

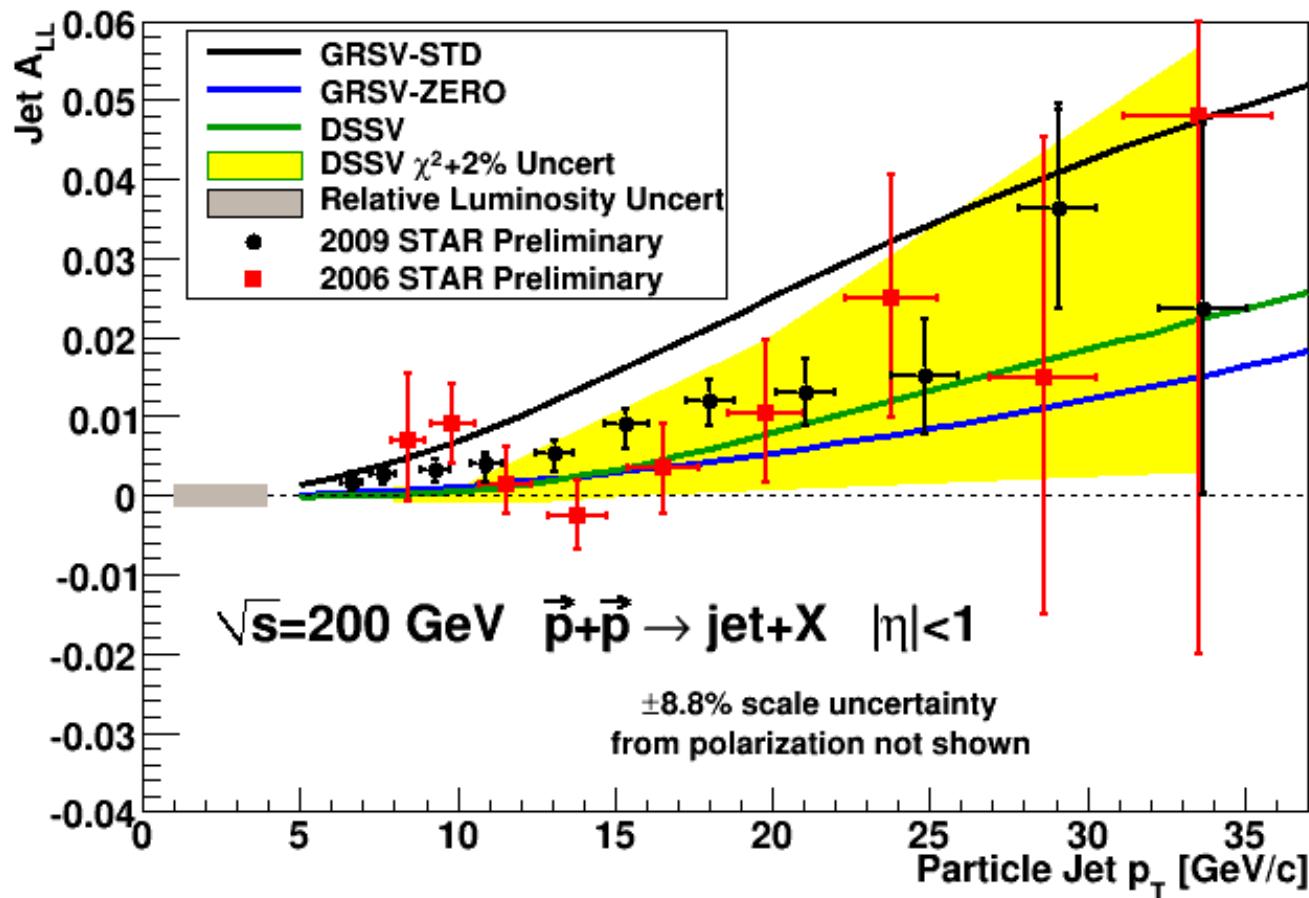
2) RHIC beam energy scan (BES)

- Search for the *QCD critical point*
- Chiral symmetry restoration

The QCD Phase Diagram and High-Energy Nuclear Collisions

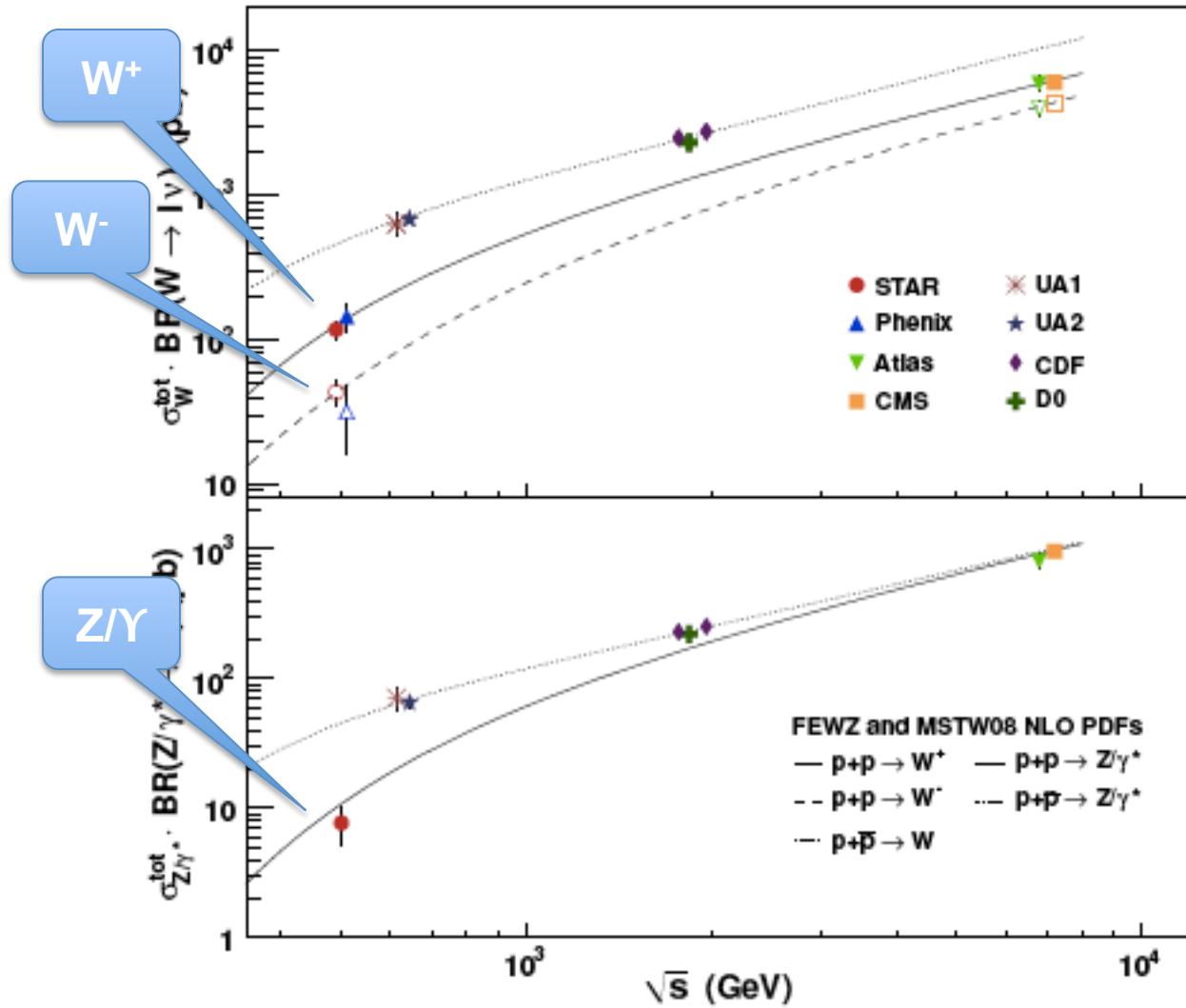


STAR A_{LL} from 2006 to 2009



2009 STAR A_{LL} measurements:

Results fall between predictions from DSSV and GRSV-STD

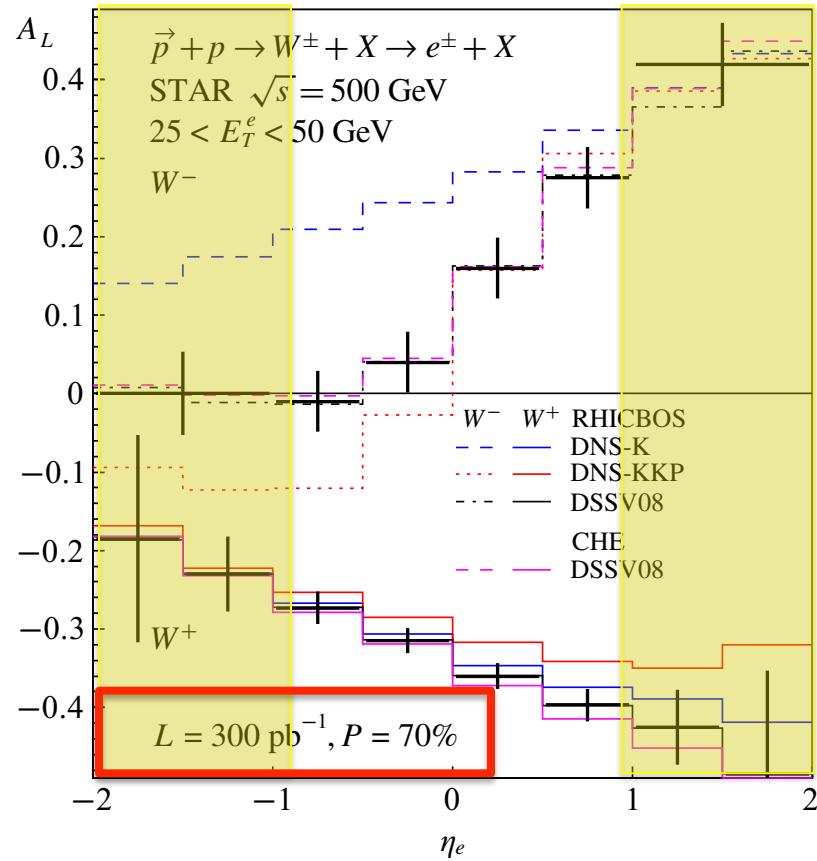
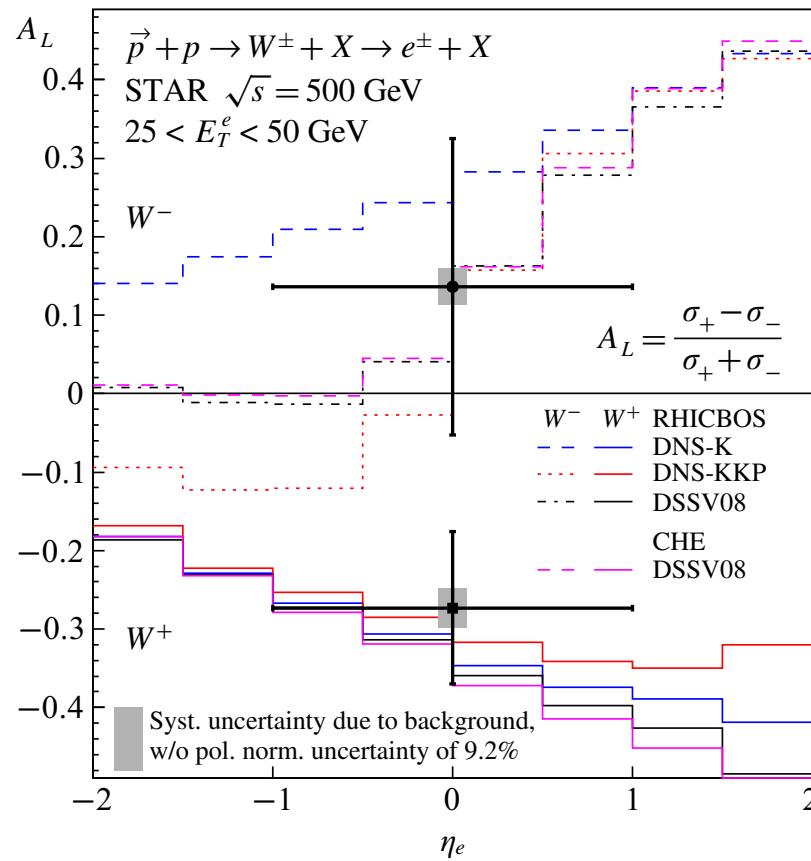


p+p collisions at
 $\sqrt{s} = 500$ GeV

- 1) Results from NLO QCD models are consistent with STAR new data
- 2) Future high statistics W data important for flavor asymmetry of the sea quark study

* Submitted to PRD soon

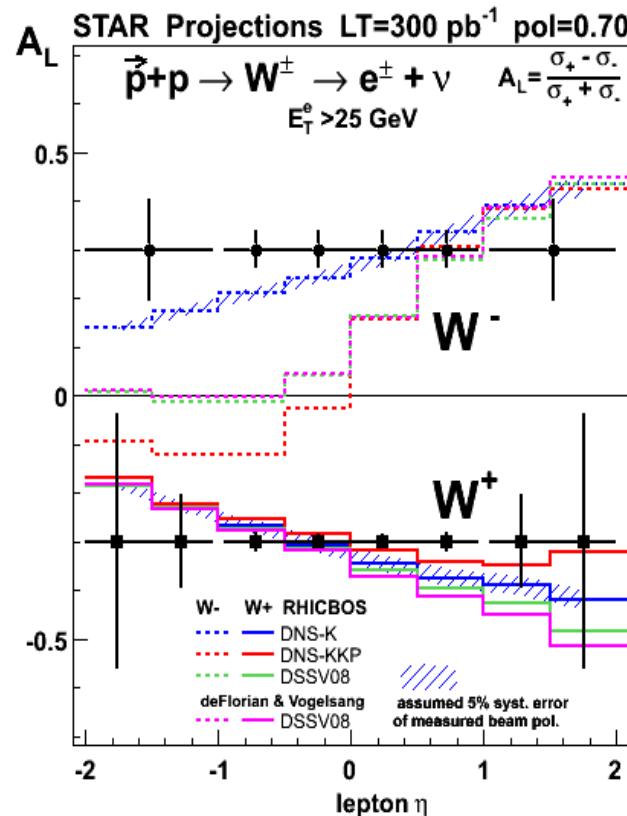
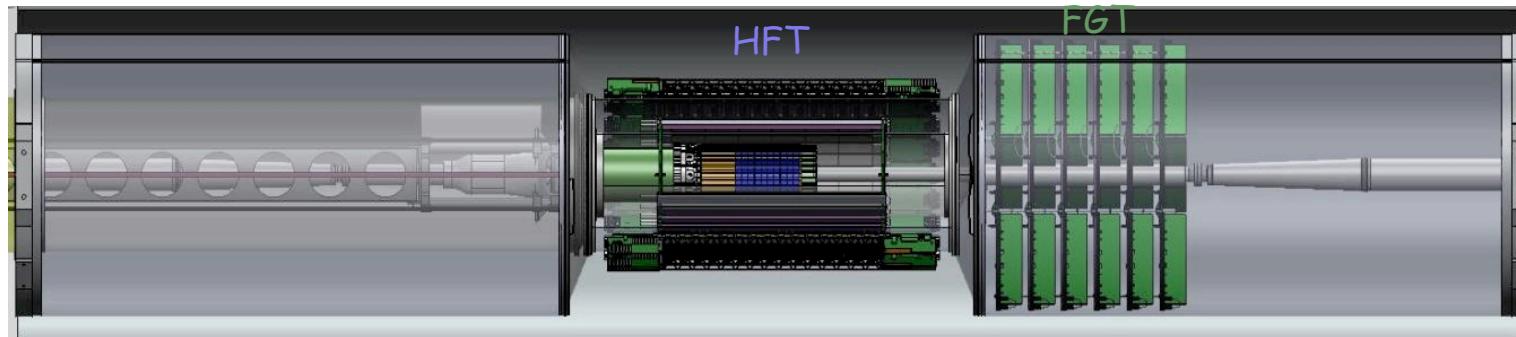
Quark Flavor Measurements: W^\pm



- 1) Results* are consistent with model: **Universality of the helicity distr. Funct.!**
- 2) Combined results of Run 9 and Run 11 reduces the error ~ 0.63 .
- 3) Precision measurements require **large luminosity, high polarization** at RHIC!

* STAR: Phys. Rev. Lett. **106**, 062002(2011).

Forward GEM Tracker



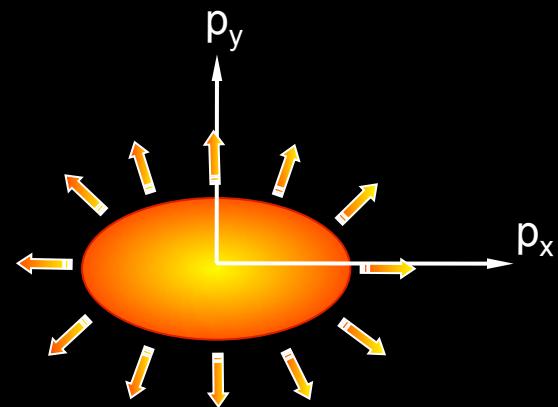
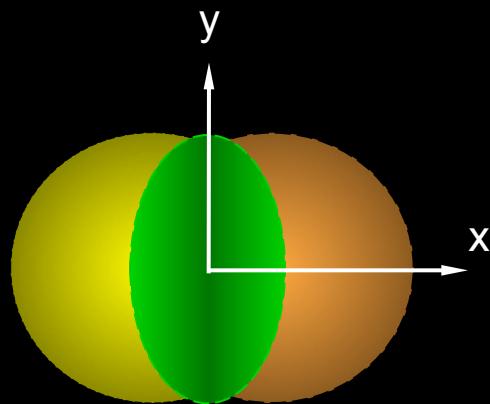
- 1) FGT: RHIC CE project
 - 2) Six light-weight triple-GEM disks
 - 3) New mechanical support structure
 - 4) Planned installation: Summer 2011

 - 1) Full charge-sign discrimination at high- p_T
 - 2) Design polarization performance of **70% or better** to collect at least 300pb⁻¹
 - 3) **Ready* for Run 12!**
- * minimal configuration

Anisotropy Parameter v_2

coordinate-space-anisotropy

↔ momentum-space-anisotropy

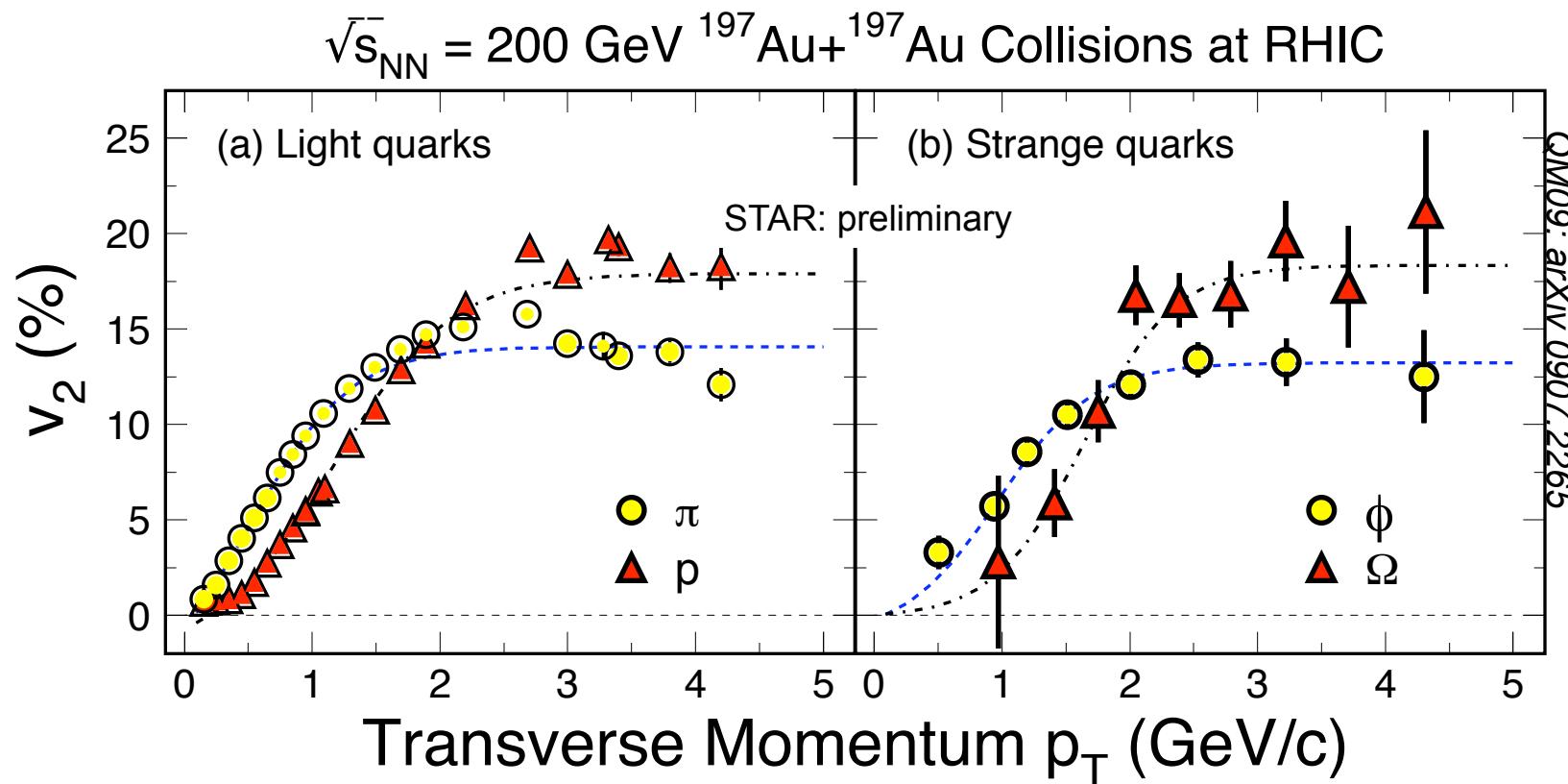


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC

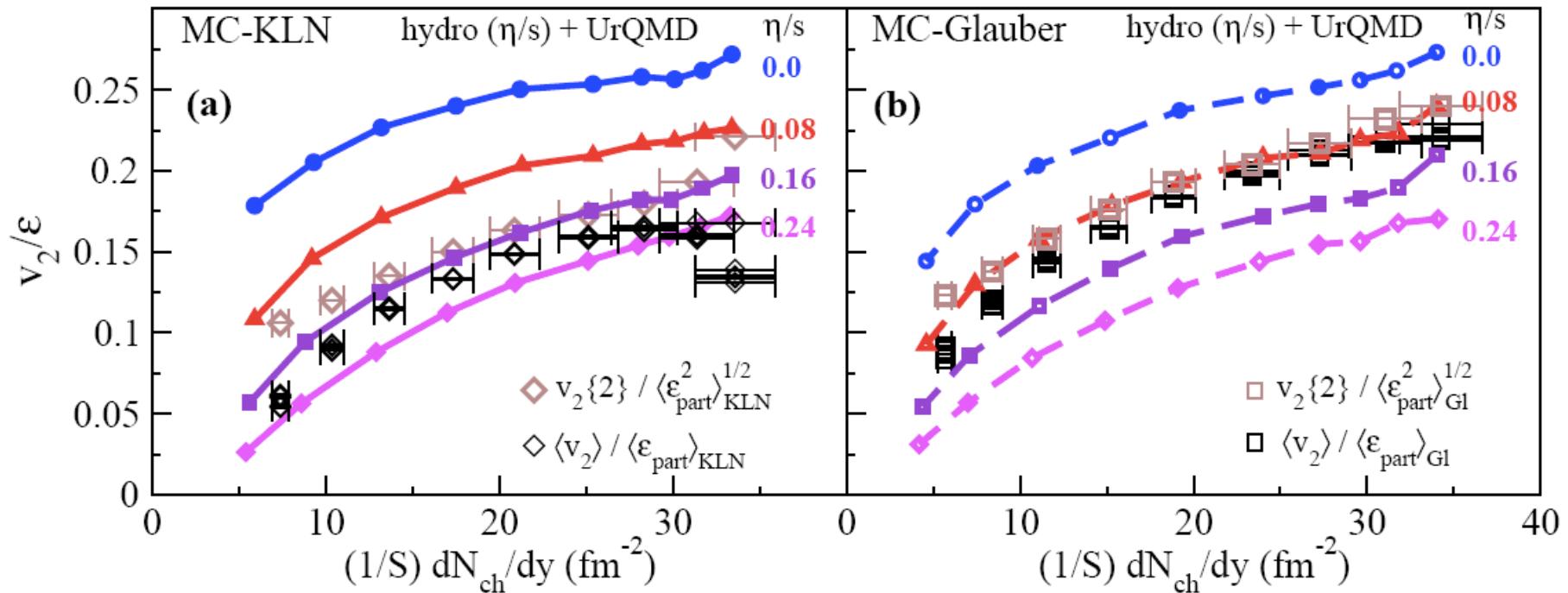


Low p_T ($\leq 2 \text{ GeV/c}$): hydrodynamic mass ordering

High p_T ($> 2 \text{ GeV/c}$): **number of quarks scaling**

- **Partonic Collectivity, necessary for QGP!**
- **De-confinement in Au+Au collisions at RHIC!**

Comparison with Model



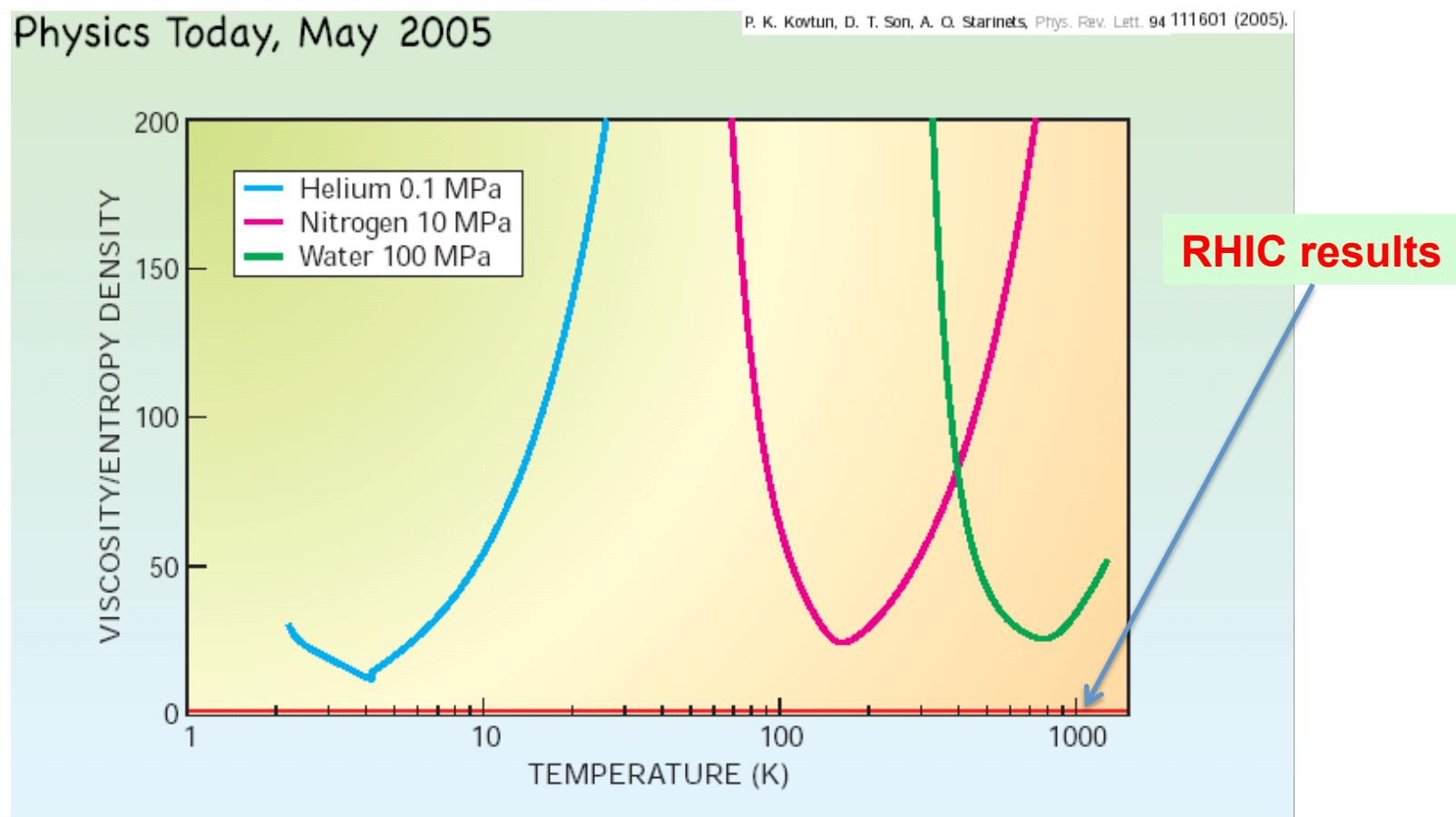
- Small value of specific viscosity over entropy η/s
- Model uncertainty dominated by initial eccentricity ε

Model: Song *et al.* *PRL*106, 192301(2011)
arXiv:1011.2783

Low η/s for QCD Matter at RHIC

Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).



- 1) $\eta/s \geq 1/4\pi$
- 2) $\eta/s(\text{QCD matter}) \ll \eta/s(\text{QED matter})$

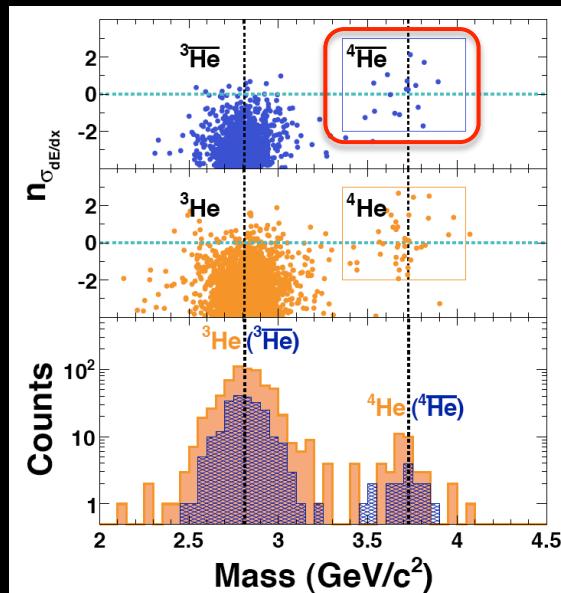
nature

April, 2011

“Observation of the Antimatter Helium-4 Nucleus”

by STAR Collaboration

Nature, 473, 353(2011).



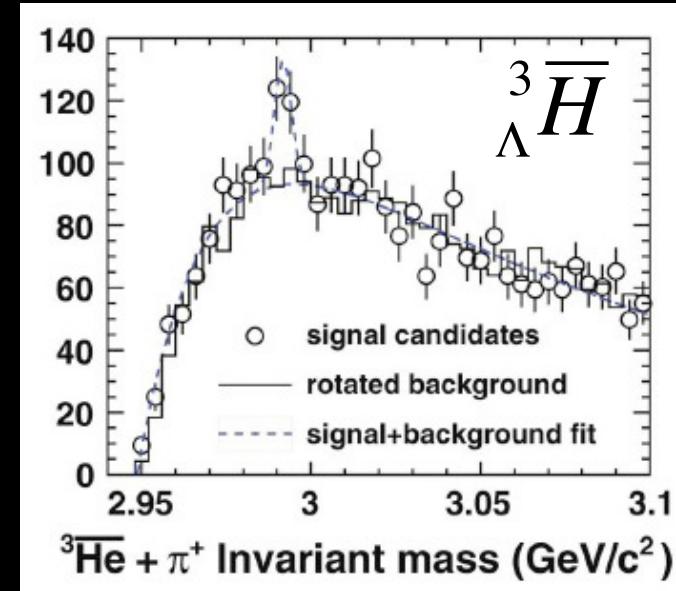
Science

March, 2010

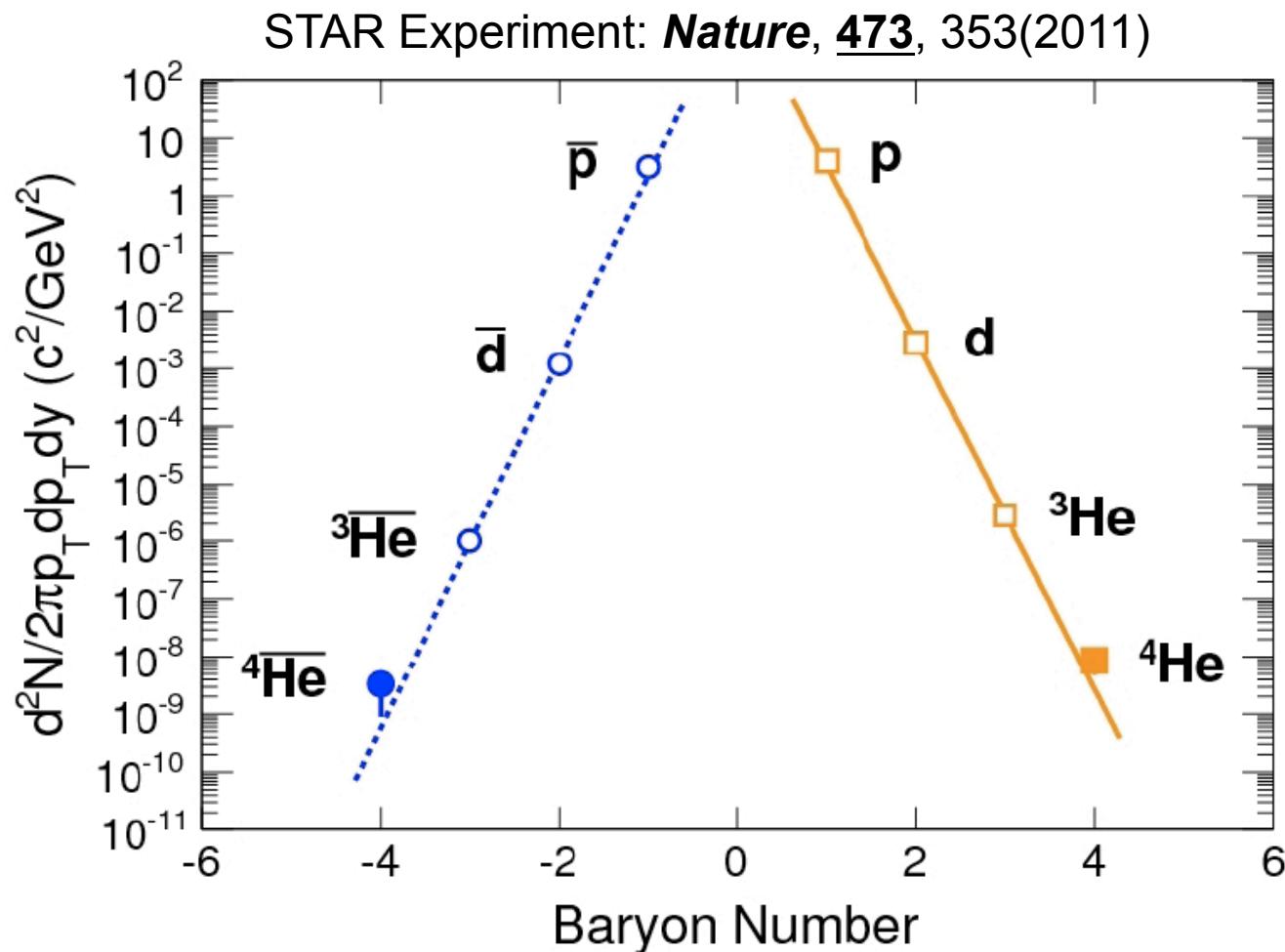
“Observation of an Antimatter Hypernucleus”

by STAR Collaboration

Science, 328, 58(2010).



Light Nuclei Productions at RHIC

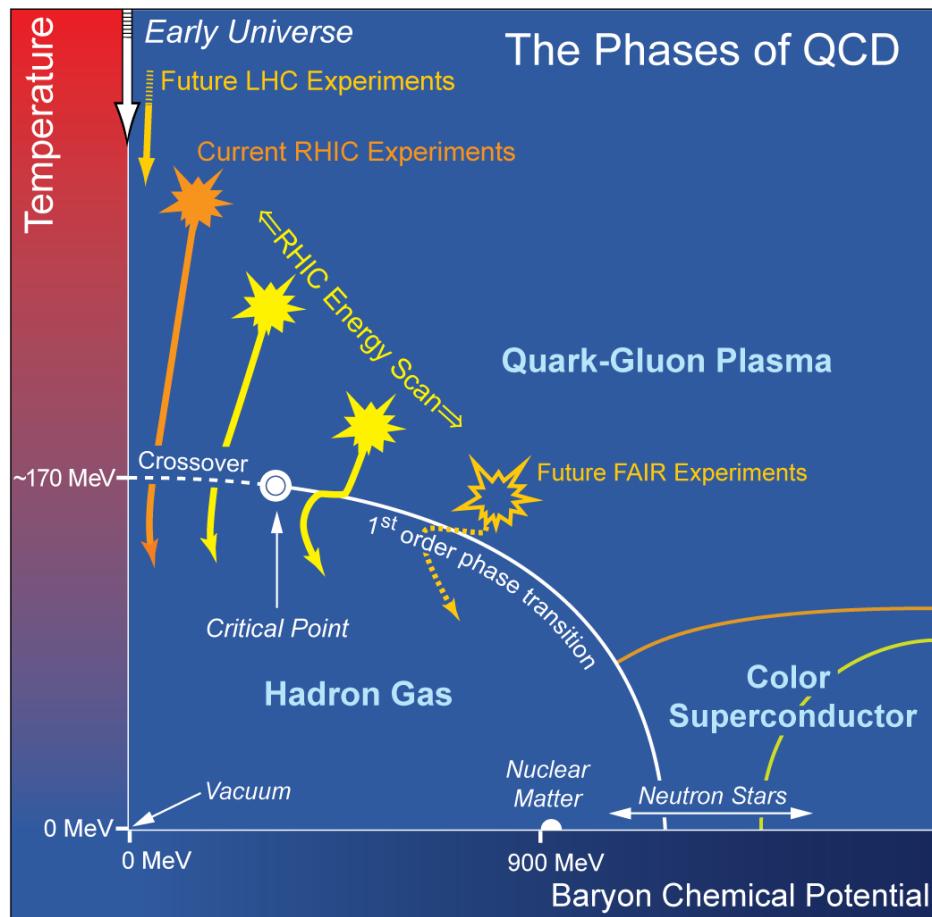


- 1) In high-energy nuclear collisions, $N(d) \gg N(\alpha)$:
sQGP → form (anti)light nuclei via coalescence
- 2) In the Universe, $N(d) \ll N(\alpha)$: $N(\text{anti-}\alpha)$?

Beam Energy Scan at RHIC

Study QCD Phase Structure

- Signals of phase boundary
- Signals for critical point

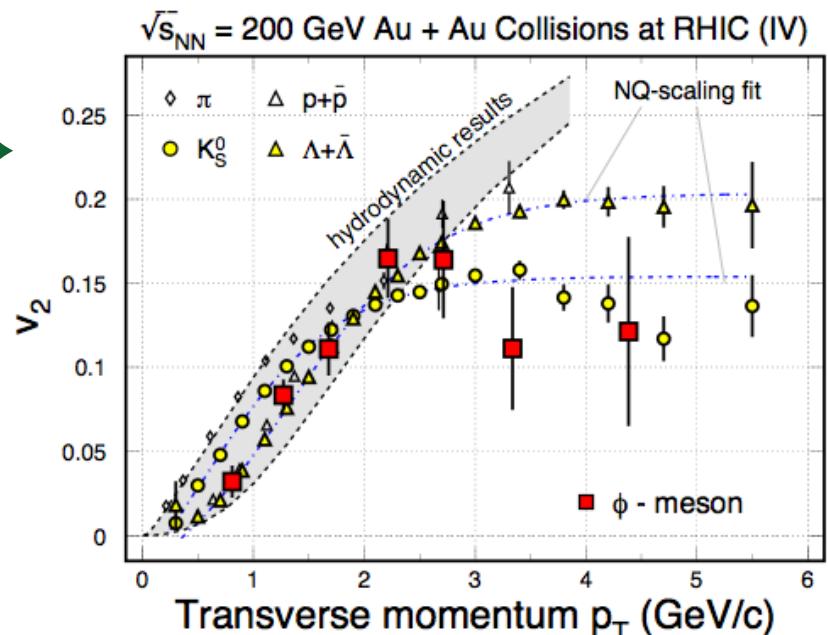
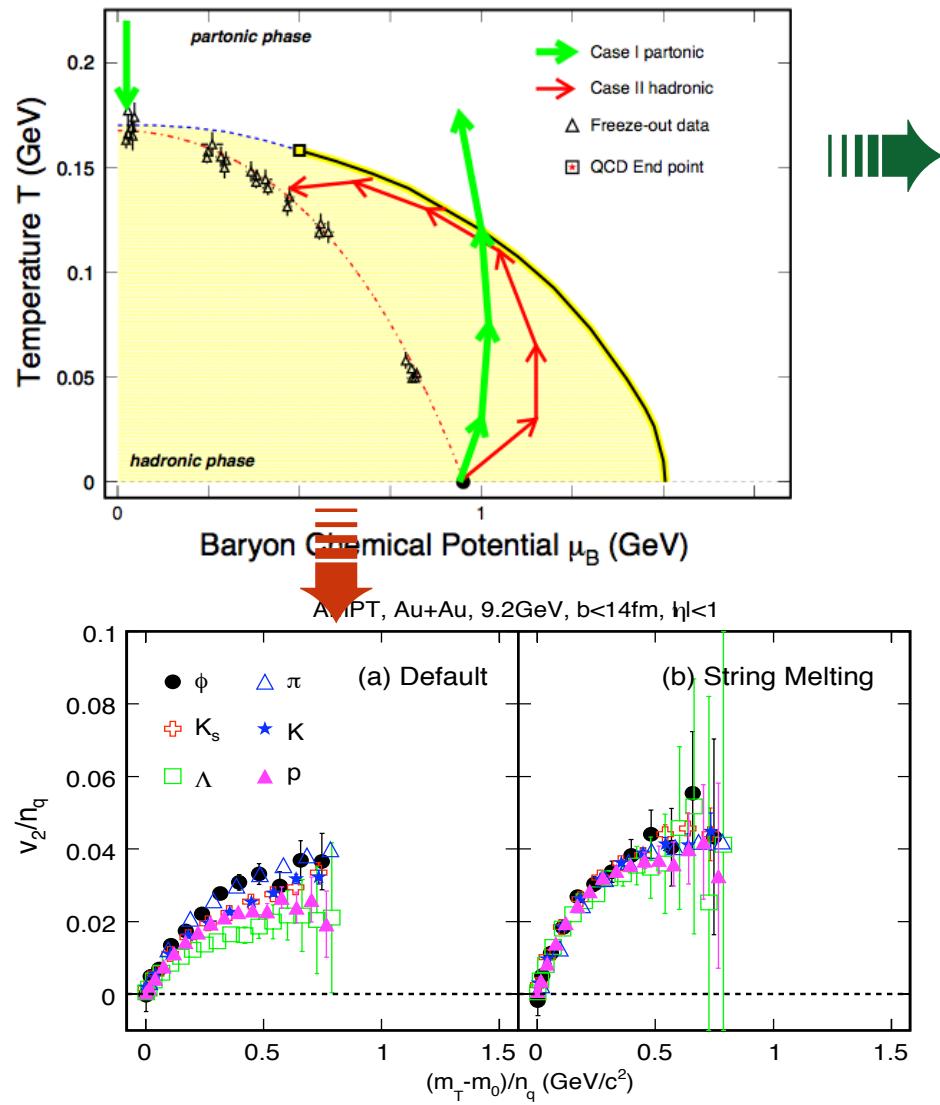


Observations:

- (1) v_2 - NCQ scaling:**
partonic vs. hadronic dof
- (2) Dynamical correlations:**
partonic vs. hadronic dof
- (3) Azimuthally HBT:**
1st order phase transition
- (4) Fluctuations:**
Critical point, correl. length
- (5) Directed flow v_1**
1st order phase transition

- <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>
- arXiv:1007.2613

Observable*: NCQ Scaling in v_2



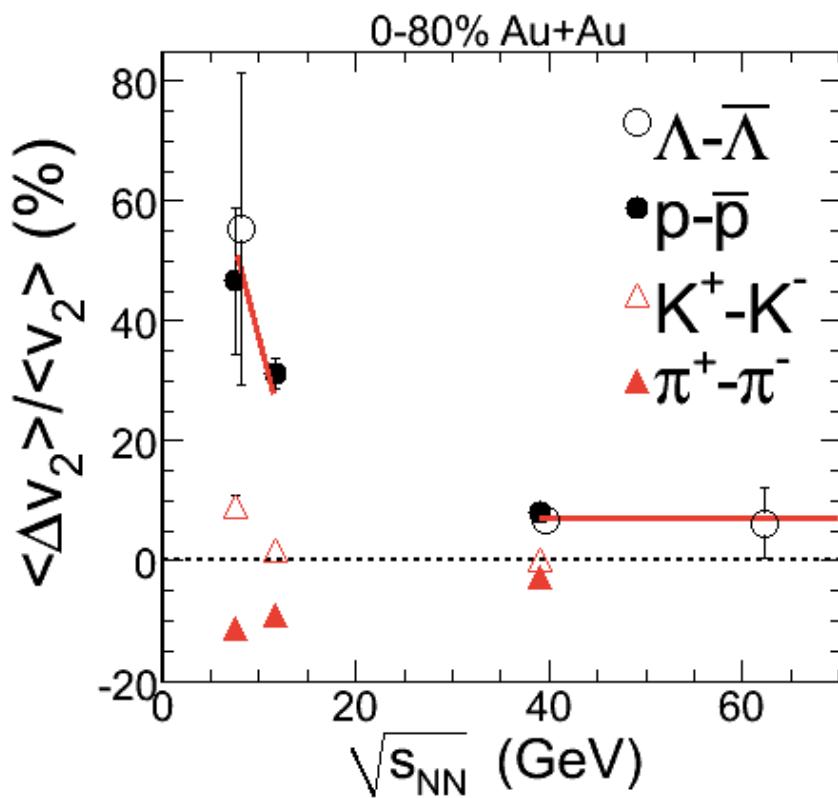
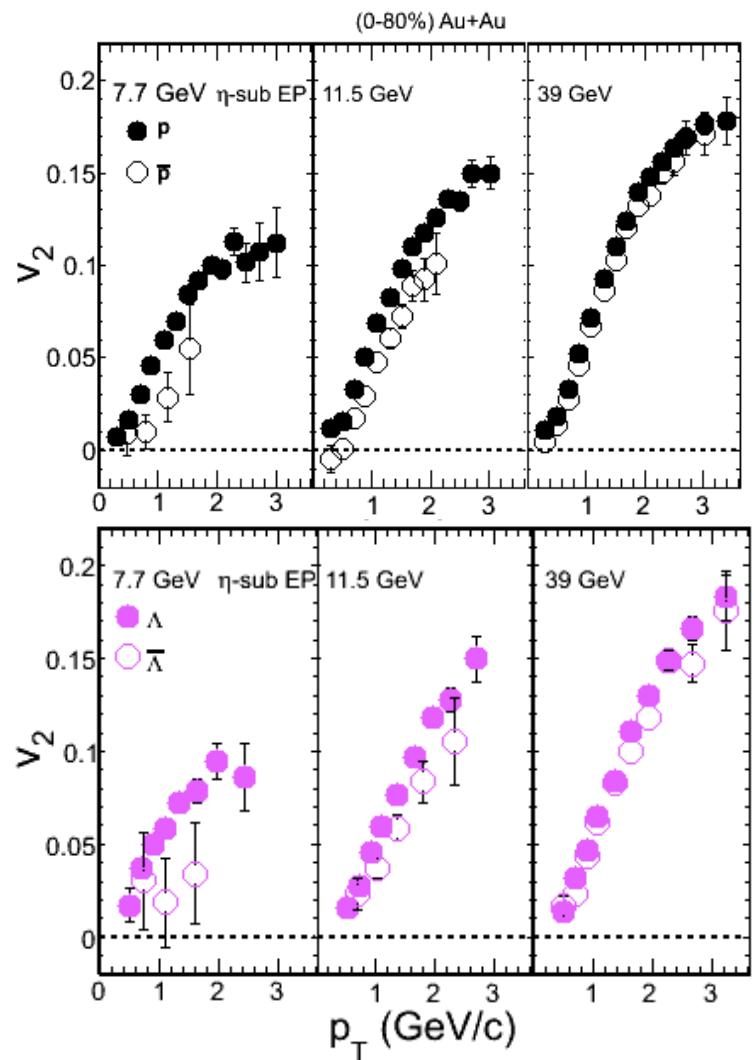
- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$ not $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of ϕ will be small.

* Thermalization is assumed!

STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

Particle and Anti-Particle v_2 vs. $\sqrt{s_{NN}}$



At $\sqrt{s_{NN}} \leq 11.5$ GeV:

- v_2 (baryon) > v_2 (anti-baryon)
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

STAR: Quark Matter 2011

Hadronic interactions are dominant



Susceptibilities and Moments



Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2} \sum_i d_i (m_i/T)^2 K_2(m_i/T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q)/T]$$

The susceptibility: $T^{n-4} \chi_q^{(n)} = \frac{1}{T^4} \frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_c}, \frac{\mu_q}{T}\right) \Big|_{T=T_c}, \quad q = B, Q, S$

$$\chi_q^{(1)} = \frac{1}{VT^3} \langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3} \langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3} \langle (\delta N_q)^3 \rangle$$

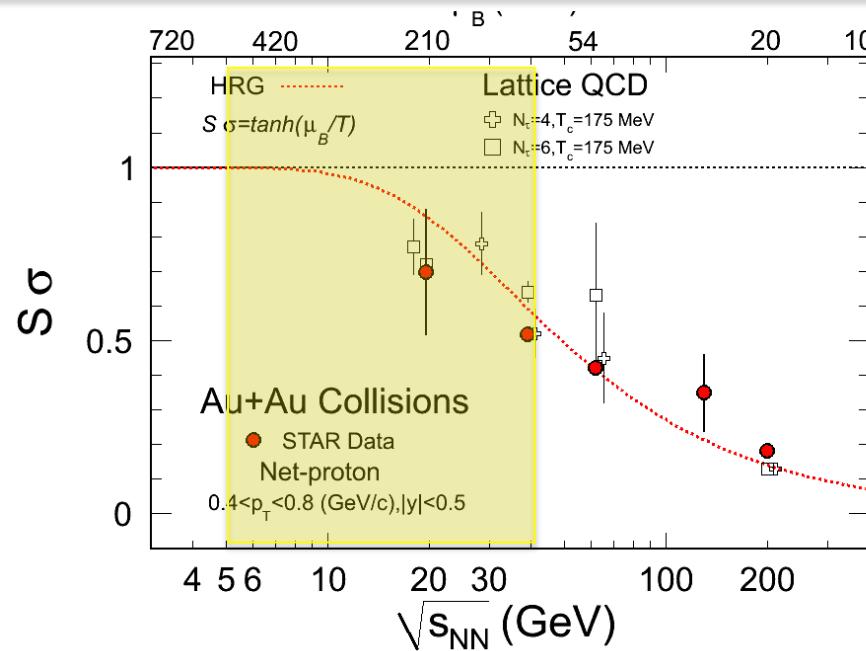
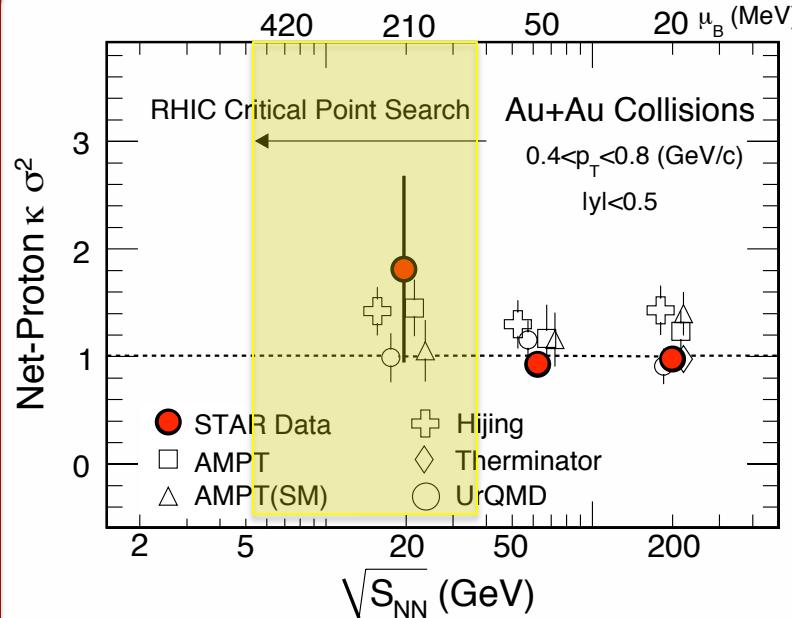
$$\chi_q^{(4)} = \frac{1}{VT^3} \left(\langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2 \right)$$

$$\begin{aligned} \frac{T^2 \chi_q^{(4)}}{\chi_q^{(2)}} &= \kappa \sigma^2 \\ \frac{T \chi_q^{(3)}}{\chi_q^{(2)}} &= S \sigma \end{aligned}$$

Conserved
Quantum
Number

Thermodynamic function \Leftrightarrow Susceptibility \Leftrightarrow Moments
Model calculations, e.g. LGT, HRG \Leftrightarrow Measurements

High Moments: Critical Point Search



- Measure conserved quantities, B , s , and Q
 - First: High order fluctuation results consistent with thermalization
 - First: Tests the *long distance QCD* predictions in hot/dense medium
- Caveats:** (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out...

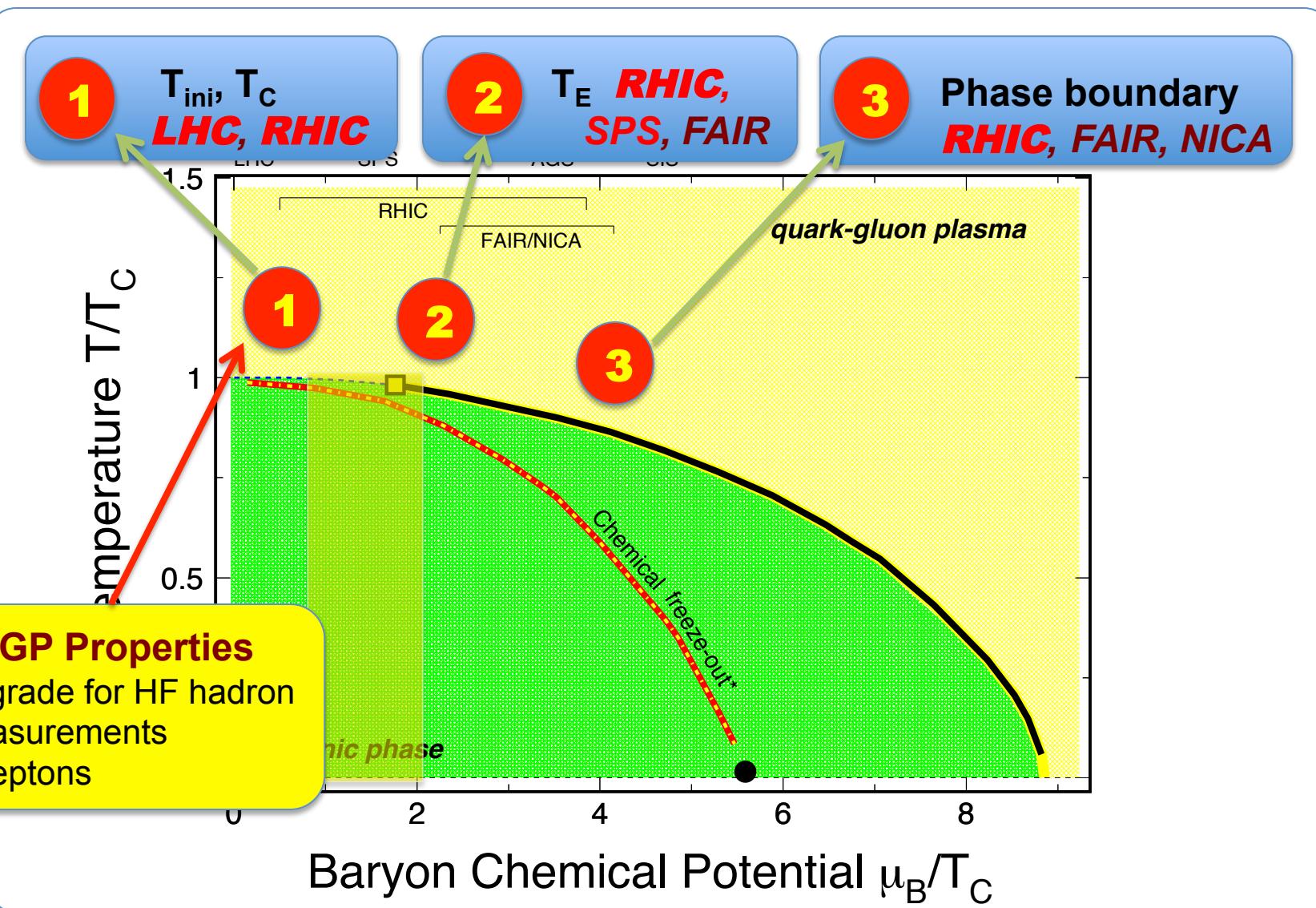
- R. Gavai, S. Gupta, 1001.3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.



Summary on Selected Results

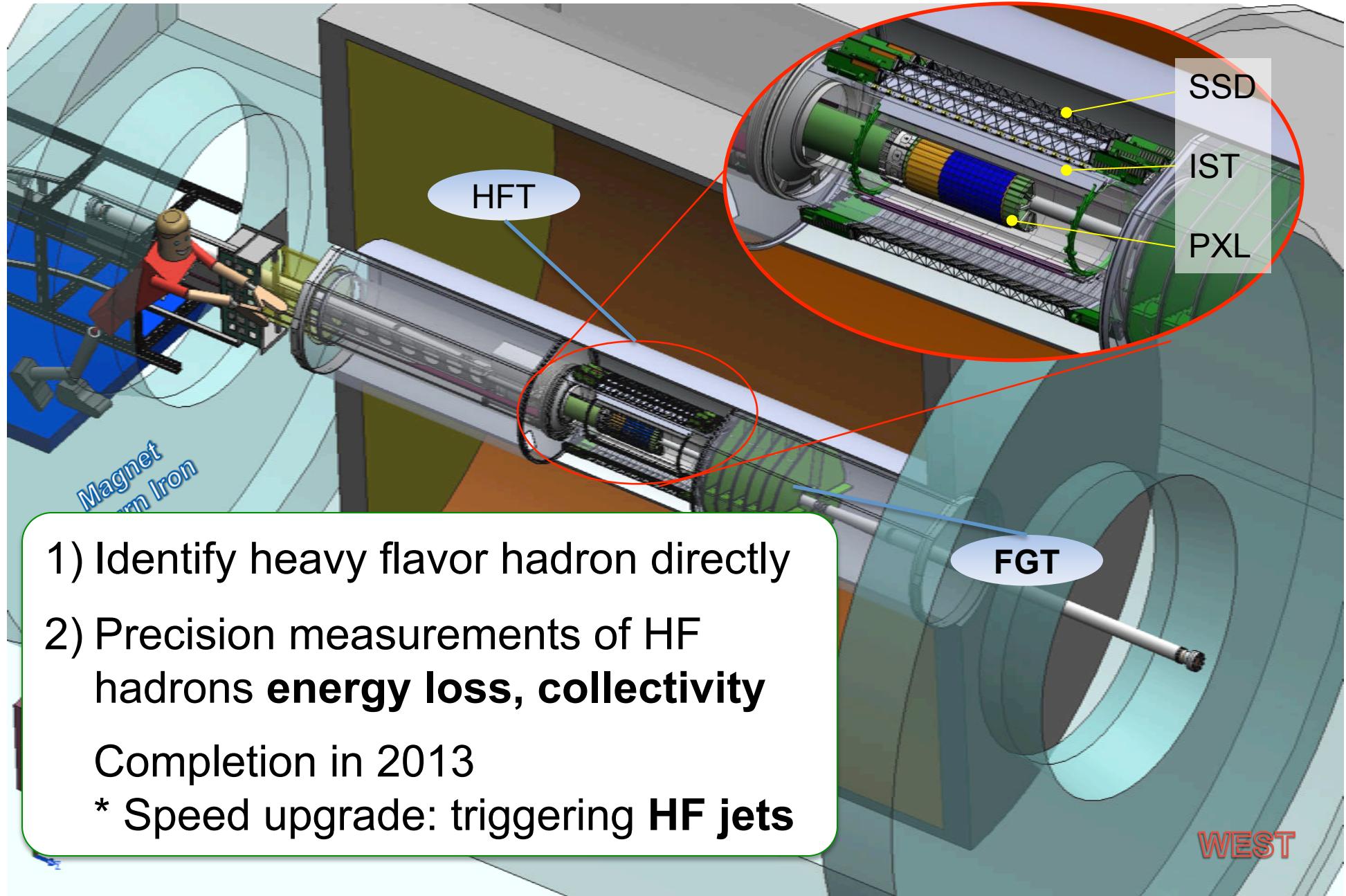


- (1) Spin: lots of progresses have been made in understanding proton helicity structure
- (2) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of freedom and collectivity***, has been formed:
 - Matter behavior like a *quantum liquid* with small η/s ($_{^3\Lambda}H, _{^3\Lambda}He$)
 - Partonic matter → antimatter:
- (3) **BES**: [partonic] $< \mu_B \sim 110\text{--}320 \text{ (MeV)}$ < [hadronic]
- (4) Net-proton distributions are consistent with LGT results. Crossover temperature: $T_C = 175^{+1}_{-7} \text{ (MeV)}$

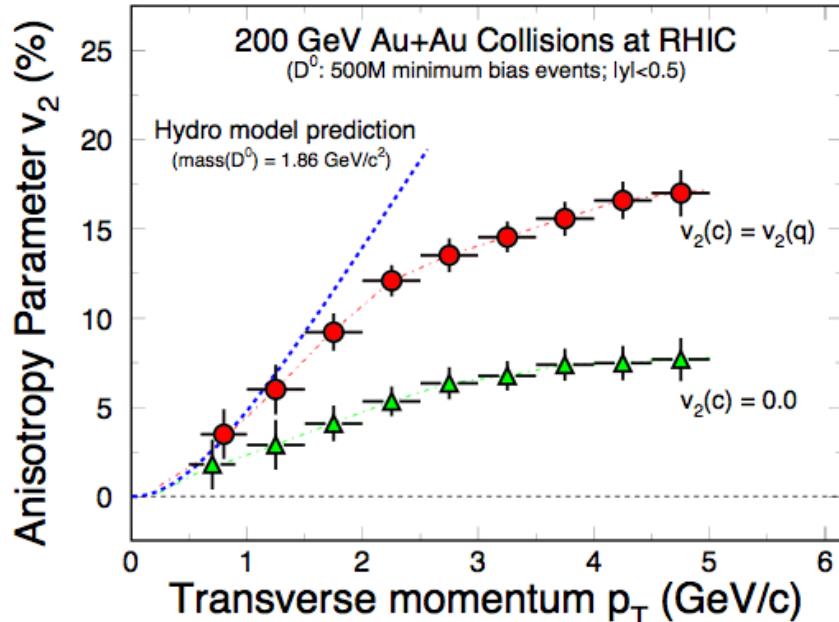




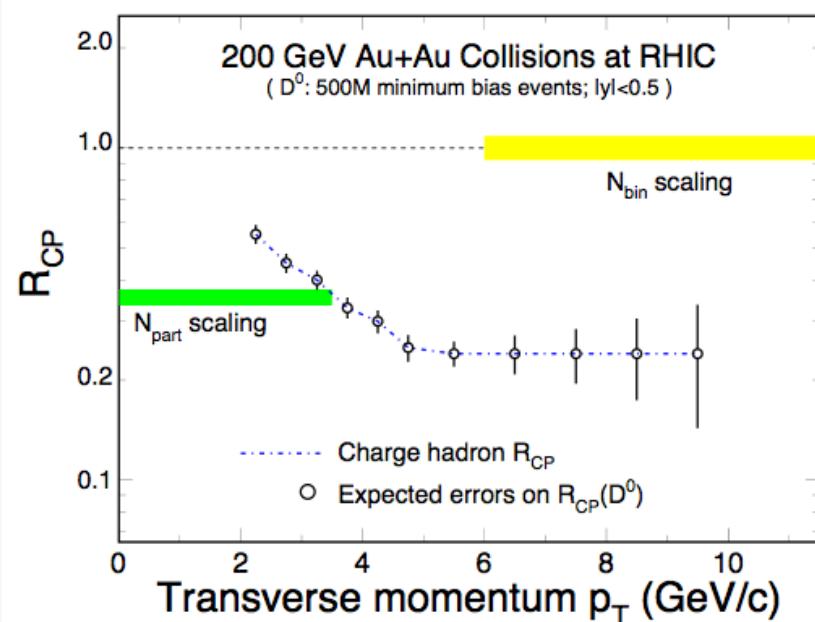
Heavy Flavor Tracker (HFT) at STAR



HFT: Charm Hadron v_2 and R_{AA}

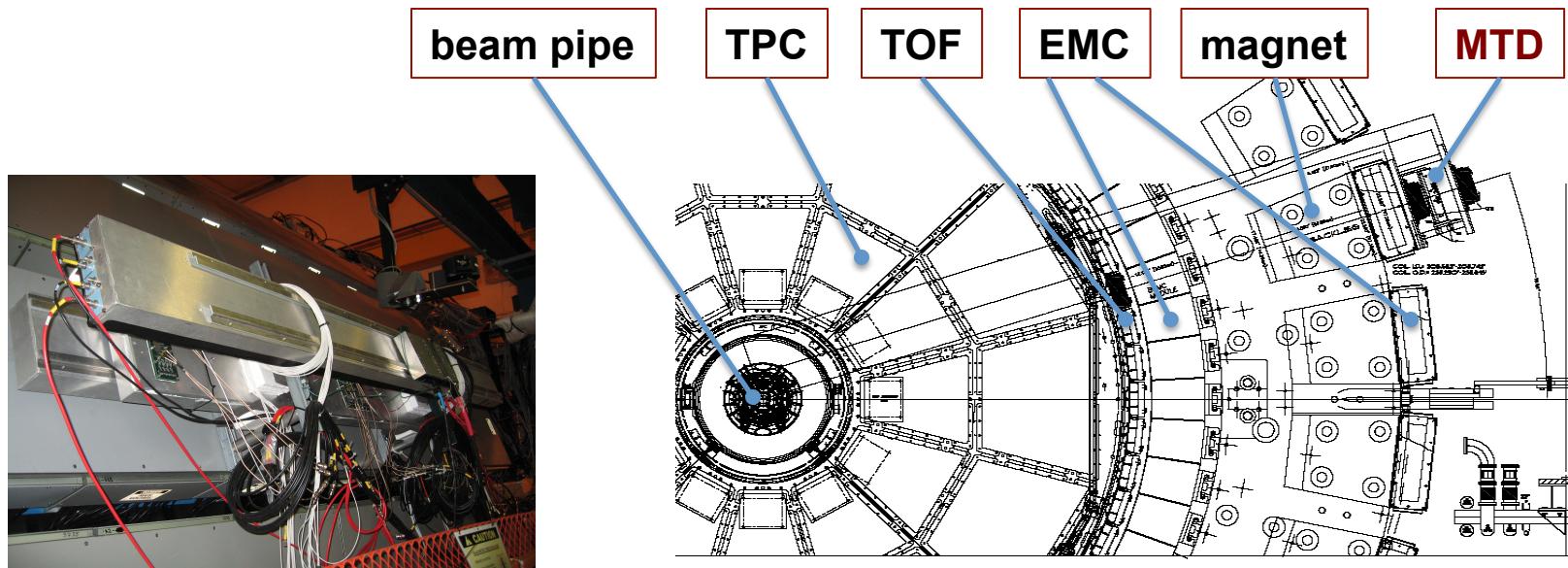


- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity \Rightarrow drag/diffusion constants \Rightarrow
- Medium properties!**
- Light quark thermalization!**



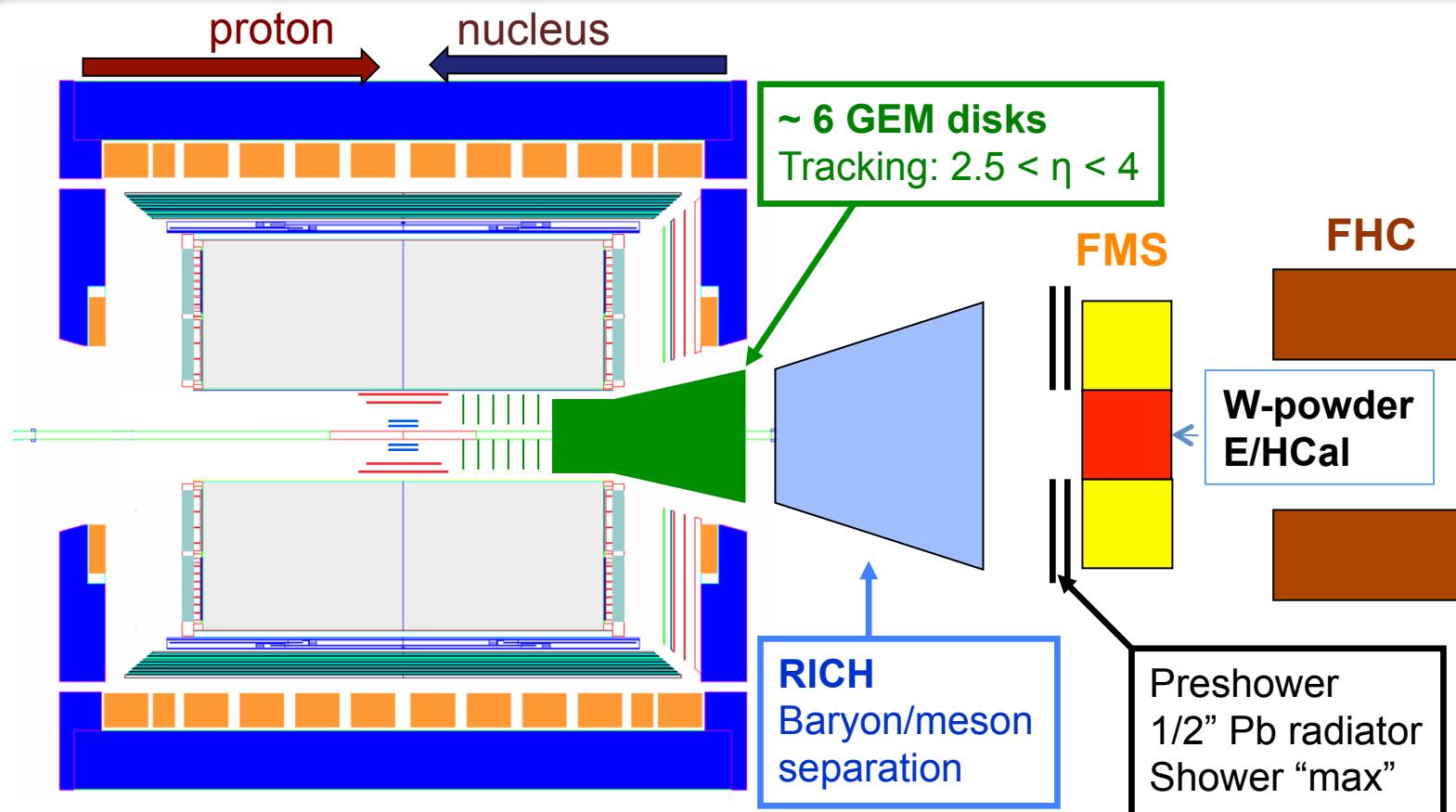
- 200 GeV Au+Au m.b. collisions ($|y|<0.5$ 500M events)
- Charm hadron $R_{AA} \Rightarrow$
- Energy loss mechanism!**
- QCD in dense medium!**

STAR: Muon Telescope Detector



Muon Telescope Detector (MTD) at STAR:

- 1) MRPC technology; $\mu_\varepsilon \sim 45\%$; cover $\sim 60\%$ azimuthally and $|y| < 0.25$
- 2) TPC+TOF+MTD: muon/hadron enhancement factor $\sim 10^{2-3}$
- 3) For high p_T muon trigger, heavy quarkonia, light vector mesons, $B \rightarrow J/\Psi + X$
- 4) China-India-STAR collaboration: completion in 2013

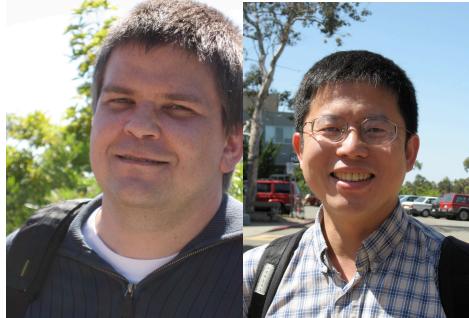


Forward instrumentation optimized for $p+A$ and **transverse spin** physics

- Charged-particle tracking
- e/h and γ/π^0 discrimination
- Baryon/meson separation
- DY measurements

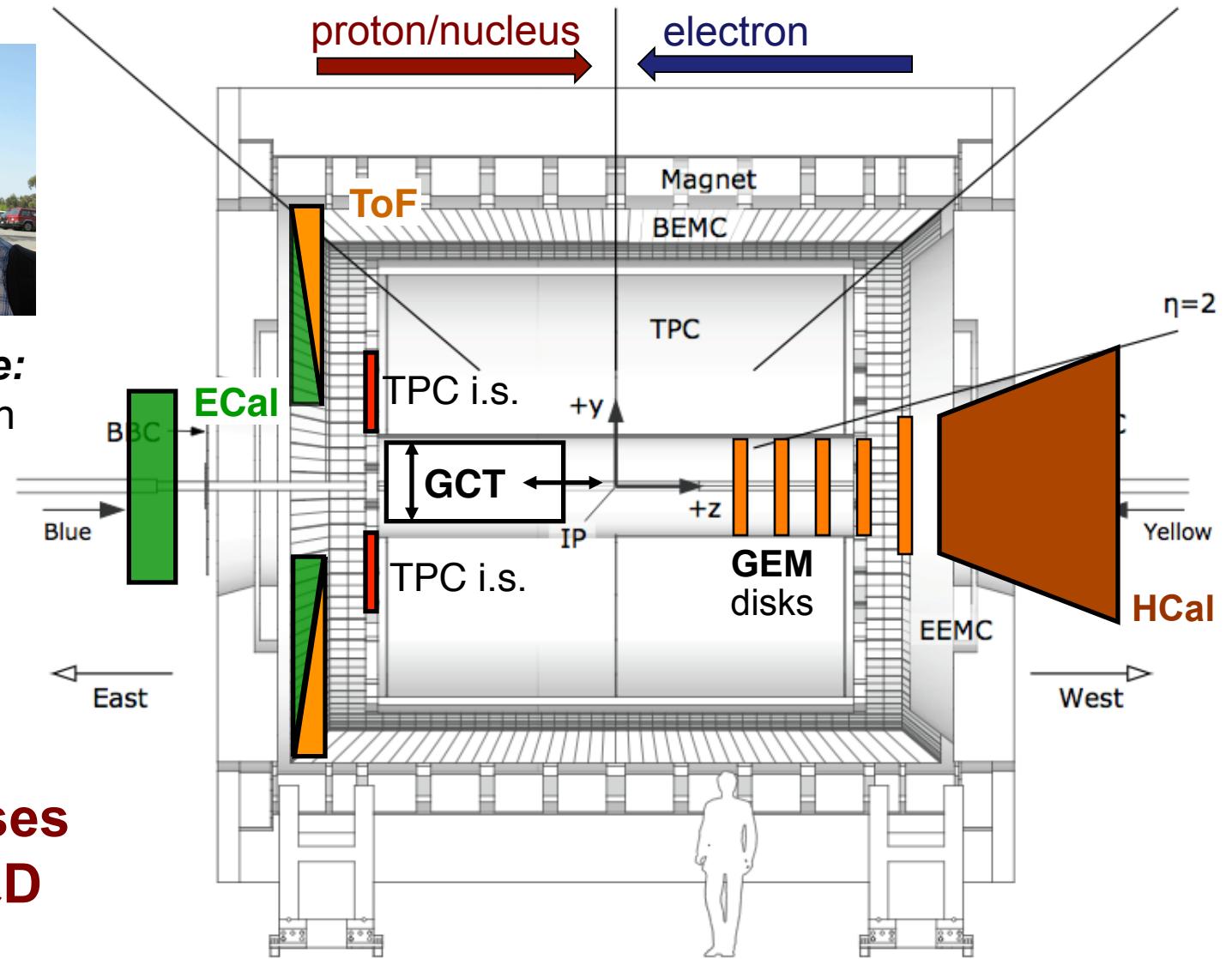
~ 2016

Outlook: from *STAR* to *eSTAR*



eSTAR Task Force:

- Ernst Sichtermann
- Zhangbu Xu



- Science Cases**
- Detector R&D**

INT Report: arXive: 1108.1713



Summary



- 1) RHIC: Dedicated facility for studying matter with QCD degrees of freedom:
 - *Properties of QGP*
 - *Sea quark and gluon contributions to proton helicity structure*
 - *QCD critical point and phase boundary*
- 2) Future: EIC (eRHIC, 2022 - ...)
 - *Partonic structures of nucleon and nuclei, i.e. nPDF*
 - *Dynamical evolution from cold nuclear matter to hot QGP*

Phase Structures of **QCD** Matter

*Many Thanks to the
Organizers!*

Nu Xu



Summary II:



sQGP formation at 200 GeV

- (1) In high-energy nuclear collisions, hot and dense ***matter***, with ***partonic degrees of freedom*** and ***collectivity***, has been formed
- (2) The matter behavior like a ***quantum liquid*** with small η/s
- (3) Partonic matter → antimatter: ${}^3\bar{H}$, ${}^4\bar{He}$

What is the structure of the QCD matter?



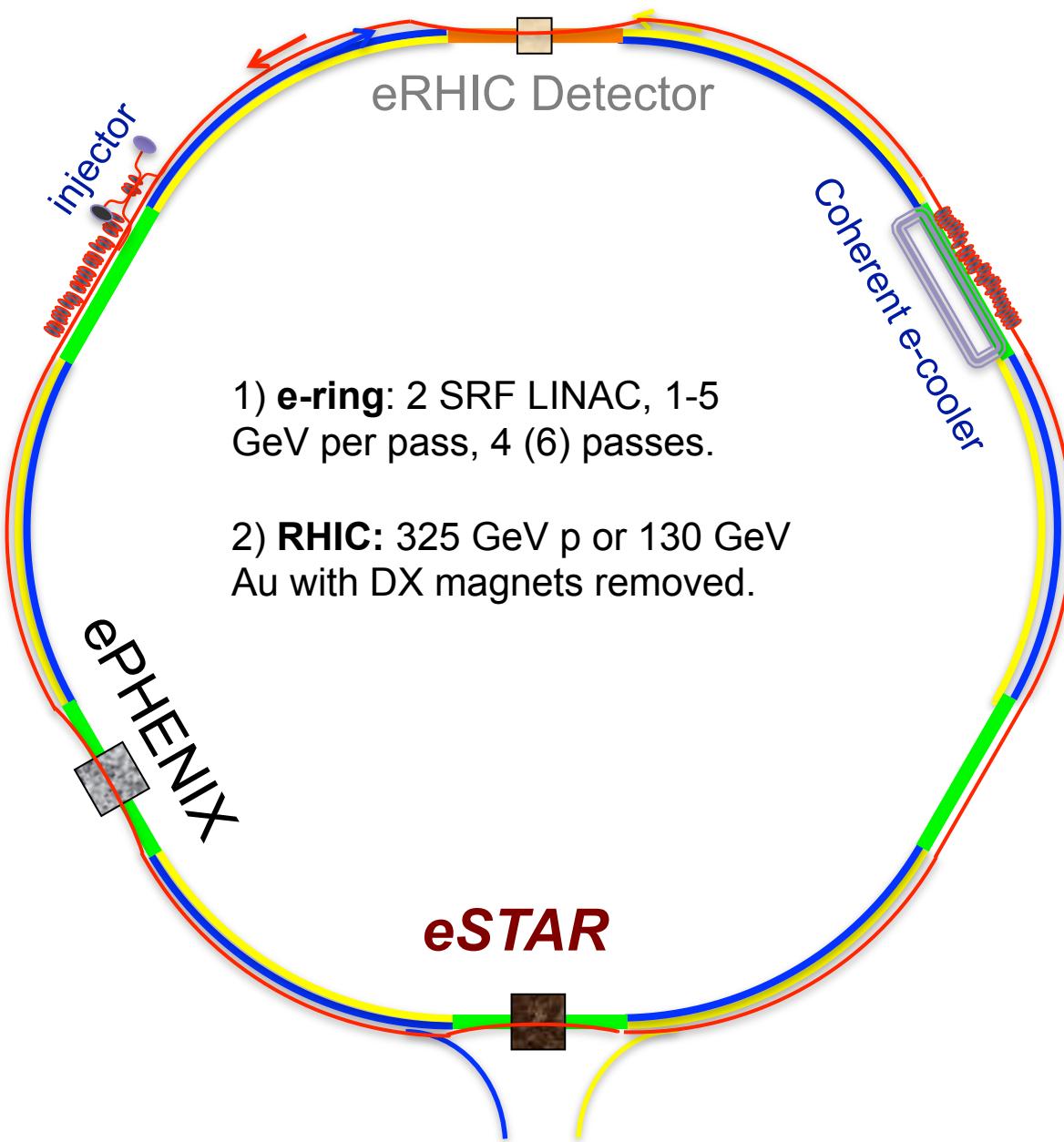
Summary II: NCQ-Scaling in v_2



- 1) Partonic collectivity in 200 GeV collisions
 - 2) At $\sqrt{s_{NN}} \leq 11.5$ GeV
 - $v_2(\text{baryon}) > v_2(\text{anti-baryon})$
 - $v_2(\phi) < v_2(\text{hadron})$
- v_2 -NCQ-scaling broken
- [hadronic] $\otimes \sqrt{s_{NN}} \leq 11.5$ GeV
- [partonic] $\otimes \sqrt{s_{NN}} \geq 39$ GeV

Where is the critical point?

Outlook: eRHIC



eRHIC:
(2022-2025)

e beam: 20-30 GeV
p beam: 325 GeV
ion beam: 130 GeV
1 dedicated detector

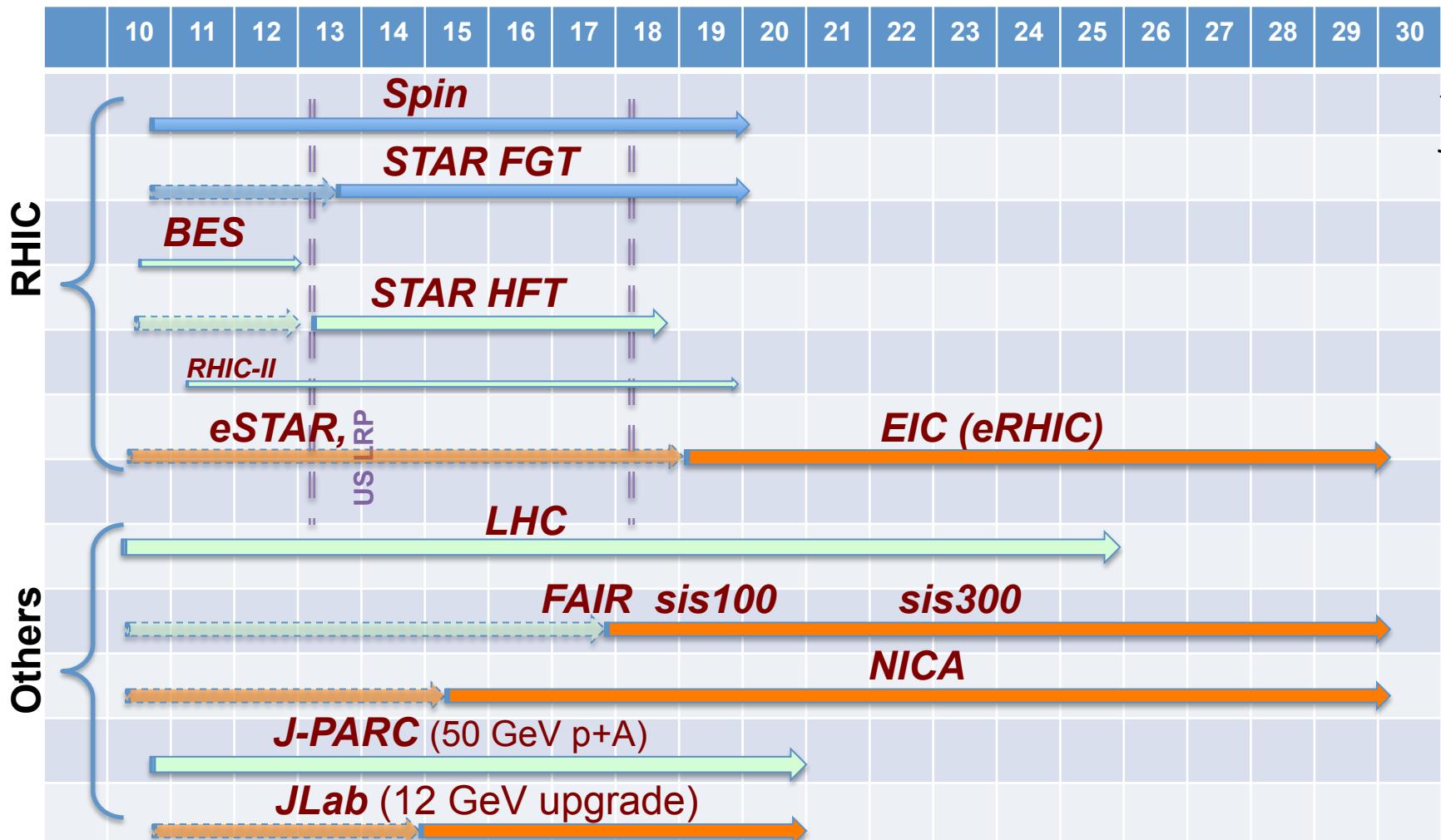
ePHENIX/eSTAR:
(2018-2022)

e beam: 5 GeV
p beam: 325 GeV
ion beam: 130 GeV

S. Vigdor: 2010 RHIC operational review

Timeline of QCD Facilities

Nu Xu, September 2009



Non-Gaussian Fluctuations

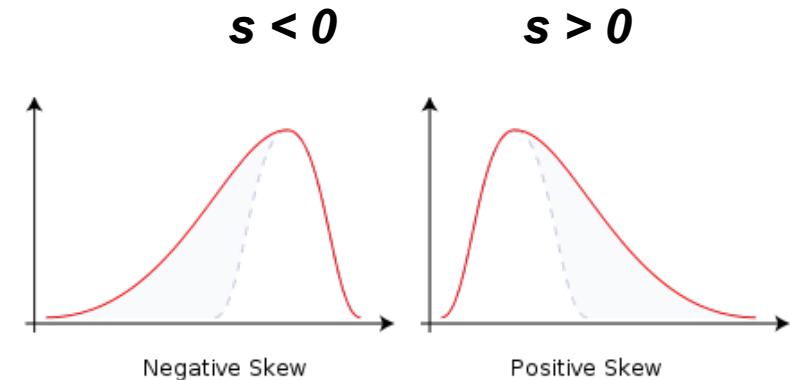
N : event by event multiplicity distribution

$$m = \langle N \rangle$$

$$\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$$

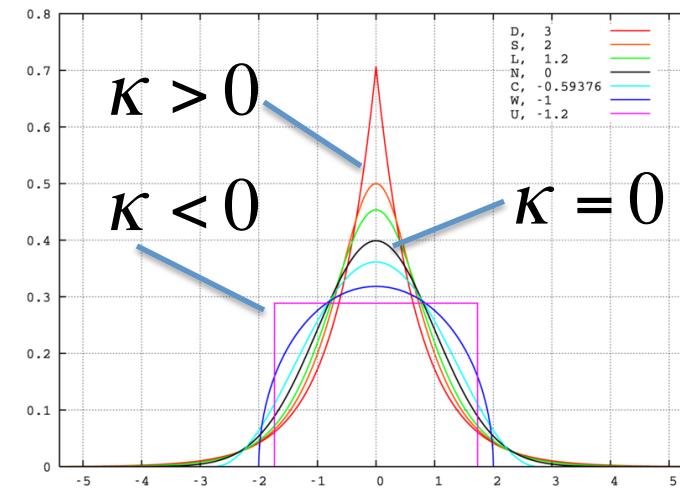
$$s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

$$\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$



For a Gaussian distribution, the $s=0$, $\kappa=0$. **Ideal probe of the non-Gaussian fluctuations at critical point.**

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena.**
Price: large number of events required.



Physics of the Heavy Flavor Tracker at STAR

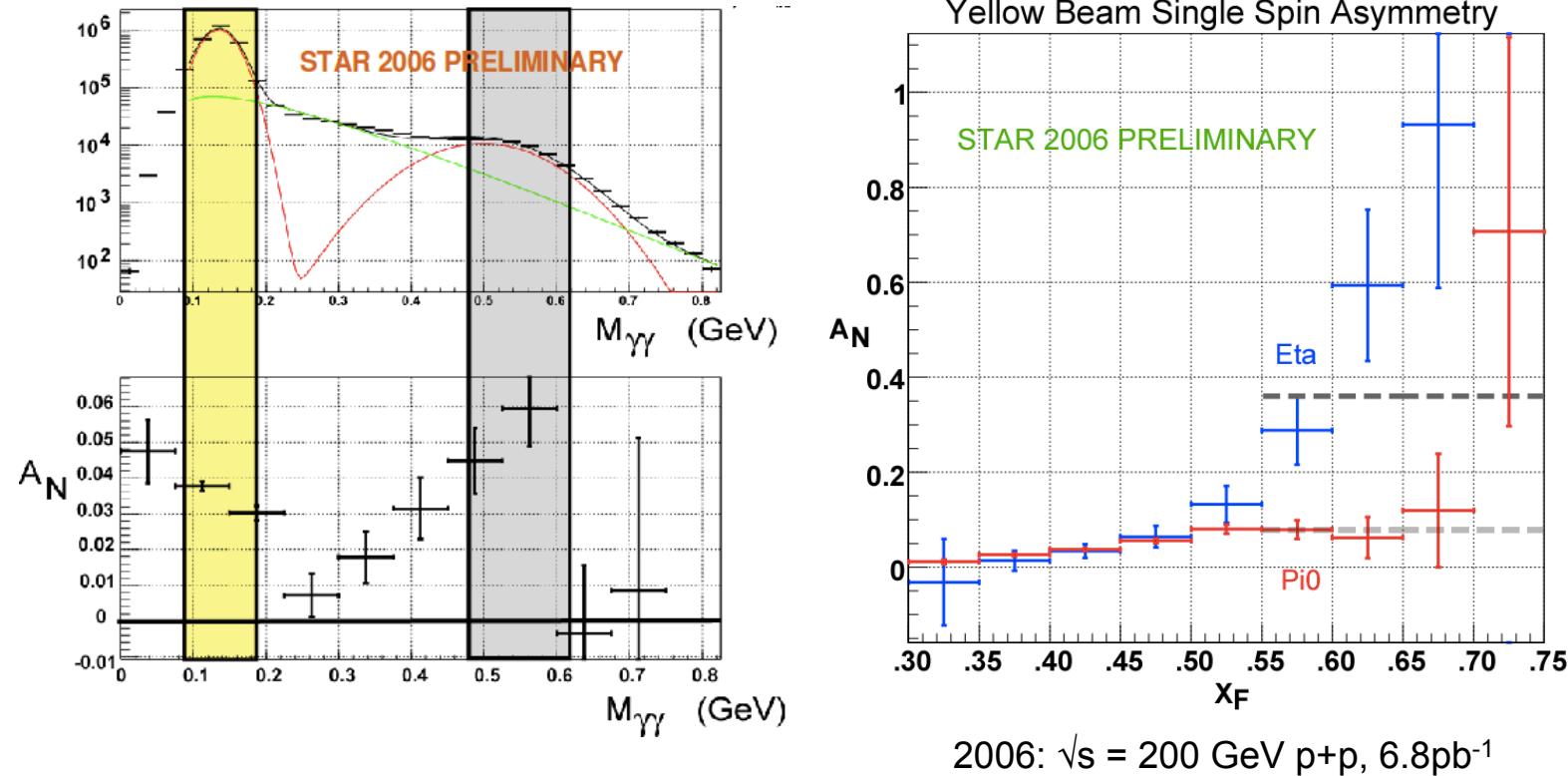
1) Direct HF hadron measurements (p+p and Au+Au)

- (1) Heavy-quark cross sections: $D^{0,\pm,*}$, D_S , Λ_C , B ...
- (2) Both spectra (R_{AA} , R_{CP}) and v_2 in a wide p_T region: 0.5 - 10 GeV/c
- (3) Charm hadron correlation functions, heavy flavor jets
- (4) Full spectrum of the heavy quark hadron decay electrons

2) Physics

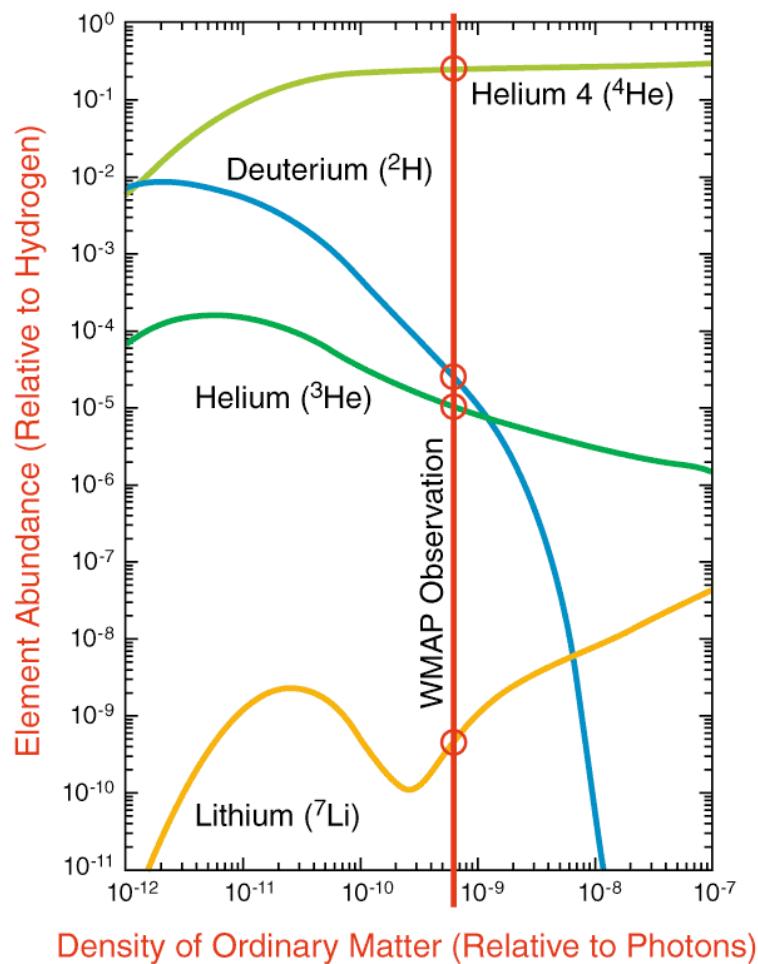
- (1) Measure heavy-quark hadron v_2 , heavy-quark collectivity, to study the medium properties **e.g. *light-quark thermalization***
- (2) Measure heavy-quark energy loss to study pQCD in hot/dense medium
e.g. *energy loss mechanism*
- (3) Measure di-leptons to study the ***direct radiation*** from the hot/dense medium
- (4) Analyze ***hadro-chemistry including heavy flavors***

Single Spin Asymmetry A_N of π^0 , η



- At $x_F = 0.55$, $\langle \eta \rangle \sim 3.7$, $A_N(\eta) > A_N(\pi^0)$ has been observed
- Production cross section for both mesons are under study

Atomic Nuclei Formation



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

$$\frac{n_B}{n_\gamma} \approx 10^{-9}$$

